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GEM- AND LITHIUM-BEARING PEGMATITES

OF THE PALA DISTRICT, SAN DIEGO COUNTY, CALIFORNIA

By RICHARD H. JAHNS and LAUREN A. WRIGHT

Prepared in Cooperation With the United States
Geological Survey

GEM- AND LITHIUM-BEARING PEGMATITES OF THE PALA DISTRICT, SAN DIEGO COUNTY, CALIFORNIA†

By Richard H. Jahns* and Lauren A. Wright**

OUTLINE OF REPORT

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ILLUSTRATIONS

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* Professor of geology, California Institute of Technology, Pasadena, California, and geologist, U. S. Geological Survey.

** Associate mining geologist, California Division of Mines.

ILLUSTRATIONS—Continued

ABSTRACT

The Pala pegmatite district, in northwestern San Diego County, California, has been a widely known source of gem and lithium minerals. Formal mining operations began in the eighteen-seventies; but the most active period was from 1900 to 1922. By 1947 the district's total recorded mineral output was valued at about three-quarters of a million dollars. This output includes 23,480 short tons of lepidolite, 2,980 pounds of tourmaline, and 1,325 pounds of gem spodumene. Small amounts of amblygonite, beryl, feldspar, and quartz also have been mined. Deposits of lepidolite and gem minerals have been extensively worked in six mines, and many additional deposits have been prospected or mined on a small scale.

The dominant rocks of the district form parts of the southern California batholith, of probable Cretaceous age. Some older rocks, chiefly schists and quartzites, occur as screens, septa, and pendants. Both these and the igneous rocks are covered in places by surficial deposits of Quaternary age.

At least 400 pegmatite dikes are exposed in an area of about 13 square miles. Most of them trend northward and dip gently to moderately westward, and many are marked by broad bends in strike and dip. They are remarkably persistent, and range from small stringers to large dikes with bulges nearly 100 feet thick. In several places they occur as swarms of closely spaced, subparallel dikes. In some swarms these dikes branch and converge along their strike, and in places they form thick, composite bodies in which each member dike commonly retains its identity.

The pegmatites occur mainly in gabbroic rocks, and appear to have been emplaced along a well-developed set of fractures. These fractures are independent of the primary structural features of the enclosing rocks, and transect contacts between major crystalline rock units; they may well have been subhorizontal at the time of pegmatite emplacement.

Some of the pegmatites are essentially homogeneous in mineralogy and texture, but most are composed of units that plainly differ from one another in lithology. Graphic granite is the chief constituent of the outermost units, or border zones, which generally are thin, discontinuous, and fine grained. It also composes most of the adjacent, coarse-grained wall zones, which ordinarily are the thickest and most persistent of the pegmatite units. Graphic granite is particularly common in the hanging-wall parts of the dikes, but constitutes nearly the full thickness of many dikes. It appears as relict masses in the fine-grained lower parts of some dikes, but also occurs as pods and thin stringers in such fine-grained pegmatite.

Discoidal masses of coarse-grained pegmatite form the innermost zones, or cores, of many dikes. Such masses are generally thin and elongate, but more pod-like cores are present in the thick bulges of a few dikes. Some cores are composed of quartz, perthite, or an aggregate of these minerals, and others consist of quartz and giant crystals of spodumene. Spodumene of gem quality occurs wholly within the cores, and represents the relatively small amount of this mineral that has escaped all hydrothermal alteration. Lithiophilite and triphylite occur in or adjacent to some quartz-spodumene cores, and commonly have been altered to manganese- and iron-phosphate minerals.

Some of the cores are separated from nearby wall zones by one or more intermediate zones, which form discontinuous or complete envelopes. These units are present only in the largest dikes or in dikes with thick bulges, and generally are rich in coarse-grained perthite.

Fracture-filling units are widespread, and consist chiefly of quartz, albite, biotite, fine-grained muscovite, or combinations of these minerals. Some transect wall zones, but merge with inner zones. Others lie wholly within a single zone, and still others cut across entire pegmatite bodies. There are all gradations between simple open-space fillings and replacement bodies developed along fractures.

Fracture-controlled replacement bodies are superimposed upon the zonal pattern of nearly all of the pegmatites. They are composed mainly of albite, quartz, and muscovite, and, less commonly, of lepidolite and tourmaline. Such bodies are most easily recognized where they transect wall-zone graphic granite. Similar mineral aggregates occur in the central parts of many dikes, where they generally corrode the surrounding pegmatite zone. These centrally disposed units, which commonly contain residual masses of earlier minerals, include much of the district's "pocket pegmatite," a rock type composed mainly of fine- to coarse-grained quartz, albite, orthoclase, microcline, muscovite, lepidolite, and tourmaline. Most of the minerals are euhedral.

All the gem tourmaline and beryl, as well as the commercial concentrations of lepidolite, occur in so-called "pocket pegmatite." Such rocks actually contain very little open space, although some cavities are partly or completely filled with a clay through which gem crystals are scattered. Pocket pegmatite occurs in cores and immediately adjacent zones, chiefly along the footwalls or in the footwall parts of the cores.

Fine-grained granitoid rocks, composed chiefly of quartz and albite, are common in the footwall parts of most dikes, and also occur locally in other parts of many dikes. Some varieties are essentially uniform in texture and structure. Others, known collectively as "line rock," are strikingly marked by alternating thin layers of garnet-rich and garnet-poor pegmatite, or of schorl-rich and schorl-poor pegmatite. Layering in some of these rocks also is caused by distinct variations in texture.

The Pala dikes are believed to have been formed by crystallization of pegmatite liquid that was injected along fractures during the final stages of consolidation of the southern California batholith. The pegmatite zones appear to have developed from the walls of the dikes inward, probably by fractional crystallization and incomplete reaction wth residual liquid. Many, if not all, of the relations in the central parts of the most complex pegmatites seem best explainable in terms of progressive accumulation and late-stage crystallization of mineralizing fluids, with accompanying deuteric replacement of earlier-formed minerals. In order to develop a few of the larger replacement bodies, material maý have been derived from other parts of the dikes, or possibly from sources farther removed. The fine-grained pegmatite units cut across the zonal structure of some dikes, and appear to have been formed in part at the expense of graphic granite. The pocket pegmatite also is at least in part of replacement origin, and is plainly younger than some of the fine-grained pegmatite.

INTRODUCTION

The lithium-bearing pegmatites [1] of the Pala district, southern California, have aroused widespread and continuing interest since their discovery about half a century ago. They have been best known to prospectors, miners, and mineral collectors as sources of gem crystals, lithium minerals, and mineral specimens of remarkable appearance and variety. Although little formal mining has been done in the district since 1922, the deposits have been visited by thousands of collectors, who have obtained from the area a large tonnage of mineral specimens. The district also has held an unusual attraction for geologists, who have advanced different theories to explain the development of pegmatites so complex in mineralogy and internal structure. It was largely on the basis of studies made in the Pala area, for example, that Waldemar T. Schaller first proposed the hydrothermal origin of much of the material in lithium-bearing pegmatites.[2]

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[1] The term "pegmatite," as herein applied, is defined as an igneous rock, generally irregular in texture, that is at least in part very coarse-grained.

[2] Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci. 5th ser., vol. 10, pp. 269-279, 1925.

Brief descriptions of the mines and minerals appeared in many journals including Mining Science, Mining and Scientific Press, and Mining World. The first systematic account of the mines themselves was published in 1905 by G. F. Kunz, whose field investigations in the district dated back to 1890.[3] The first comprehensive report on the geology of the pegmatites and the surrounding rocks was published during the same year by Waring.[4] Observations on the geology of the mines were recorded by Merrill in 1914.[5]

W. T. Schaller visited the district in 1903, and subsequently studied several of the minerals in the laboratories of the University of California. In 1904 he began a series of investigations for the U. S. Geological Survey that was to extend over a period of many years. His was the most systematic study of the district, and after his field work in 1924 he prepared three brief but important summaries.[6] Although he did much laboratory work, no general report was published. A comprehensive report on the district, with a map of the areal geology and many sketch maps and sections of individual pegmatites and mines, was prepared in manuscript form but never published.

M. G. Donnelly studied the pegmatites and made a reconnaissance geologic map of the district during the period 1933-35. His reports[7] represent the most recent geologic summaries for the district.

Recent field work by the U. S. Geological Survey in the southern California pegmatite region dates from 1943, when D. J. Fisher examined and appraised numerous deposits in Riverside and San Diego Counties as potential sources of beryllium and tantalum-columbium minerals, quartz crystals, and sheet muscovite. This wartime investigation was necessarily very brief, aimed as it was at increasing the known domestic reserves of strategic pegmatite minerals. Following the cessation of hostilities in 1945, plans were made for a thorough reinvestigation of the Pala-Rincon-Mesa Grande pegmatite belt, with special emphasis upon detailed mapping and structural studies to supplement the earlier mineralogic work of Schaller. This project, of which the study of the Pala district is a part, was started in July 1946, and has been carried on under the joint auspices of the Geological Survey and the California State Division of Mines. The field investigations were completed in April 1950.

Scope of Investigations

The study of the pegmatites and other rocks of the Pala district was made intermittently during the period July 1946-March 1948. A total of 29 weeks was devoted to field work by Jahns, and about 10 weeks to field work during the fall and winter seasons of 1946-47 by Wright. Wright was not able to participate in the laboratory work and preparation of this report, but has checked and approved the manuscript.

During the course of the field investigations, the district was mapped geologically, more than 350 pegmatite dikes were examined, one of them was mapped in detail for its entire exposed length of more than half a mile, and large parts of four other dikes were mapped. Detailed maps were made of the surface and underground workings of 16 mines, and more than 100 other mines and prospects were visited and studied. The mapping was done on several scales, ranging from 10 feet and 20 feet to the inch for most mines, through 50 feet and 100 feet to the inch for pegmatite dikes, to 660 feet to the inch for the entire district. Enlargements of aerial photographs furnished by the Agricultural Adjustment Administration were used as bases for the geologic map of the district.

In the studies of the pegmatites, emphasis was placed upon petrology and structure. Particular attention was given to the recognition and interpretation of distinctive rock units within each dike, and to such broader features as the relations between shape and attitude of the dikes and structural features in the adjacent country rock. Many of the broader features were made clearer by means of the areal geologic mapping. The field studies were supplemented by preliminary mineralogic investigations in the laboratories of the California Institute of Technology, where 84 thin-sections and more than 500 samples of crushed pegmatite were examined under the microscope. Most of the microscopic studies were aimed at identification of minerals, especially feldspars, and only preliminary work on small-scale textures and structures was undertaken. The tentative conclusions regarding paragenetic relations and the origin of the various pegmatite units are therefore based primarily upon detailed megascopic study.

The present report is in part economic in scope with emphasis on those features of the pegmatites and country rocks that bear most significantly upon the occurrence of commercially desirable minerals. Detailed descriptive mineralogy, country-rock petrography, and discussions of pegmatite genesis, for example, have been held to a minimum, whereas structure and descriptive petrology are emphasized. Not all controversial questions are analyzed in detail, but an attempt has been made, in presenting interpretations, to indicate the degree of assurance justified by the data at hand.

The eight mines which are described briefly include nearly all those from which substantial commercial production has been obtained, and were selected to provide a satisfactory coverage of the various types of pegmatites exposed in the district.

Acknowledgments

The investigations upon which this report is based were started at the suggestion of Waldemar T. Schaller of the U. S. Geological Survey, and it is a real pleasure to acknowledge his continued interest and hearty cooperation in the project. He generously supplied numerous old maps and mine descriptions, many of them prepared when the mines were in operation, and his willing counsel has been invaluable. Lincoln R. Page, Waldemar T.

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[3] Kunz, G. F., Gems, jewelers' materials, and ornamental stones of California: Calif. Min. Bur. Bull. 37, 155 pp., 1905.

[4] Waring, G. A., The pegmatyte veins of Pala, San Diego County: Am. Geologist, vol. 35, pp. 356-369, 1905.

[5] Merrill, F. J. H., Mines and mineral resources of San Diego County, California: California Min. Bur., Rept. XIV, pp. 691-700, 706-708, 1914.

[6] Schaller, W. T., op. cit., 1925.
Schaller, W. T., Mineral replacements in pegmatites: Am. Mineralogist, vol. 12, pp. 59-63, 1927.
Schaller, W. T., Pegmatites, in ore deposits of the western states, pp. 144-151, Am. Inst. Min. Met. Ore, New York, 1933.

[7] Donnelly, M. G., The lithia pegmatites of Pala and Mesa Grande, San Diego County, California: California Inst. Tech., unpubl. Ph.D. Thesis, 1935.
Donnelly, M. G., Notes on the lithium pegmatites of Pala, California: Pacific Mineralogist, vol. 3, pp. 8-12, 1936.

Schaller, and Ward C. Smith of the U. S. Geological Survey, Olaf P. Jenkins and L. A. Norman, Jr., of the California State Division of Mines, and Roy M. Kepner of the San Diego County Division of Natural Resources, visited the area and contributed many helpful ideas and suggestions. Numerous problems were discussed with John B. Hanley of the U. S. Geological Survey, who was working in the adjacent areas and who gave generously of his time in aiding the mapping of several deposits. Able field assistance was contributed from time to time by Laurence F. Gurney and Wayne E. Hall of the U. S. Geological Survey, and by Enver Altinli, Wakefield Dort, Jr., Don M. George, Jr., and Robert M. Greenwood of the California Institute of Technology.

The mine and property owners in the district have been actively cooperative. Particular thanks for many personal kindnesses are due to Mr. and Mrs. R. D. Armstrong, Mr. George Ashley, and Mr. and Mrs. Monta F. Moore, of Pala; Mrs. Frank A. Salmons of La Jolla; and Mr. Frederick M. Sickler of Bonsall.

Completion of the report was facilitated by Joan T. Rounds, who drafted the maps and sections, and by Florence Wiltse, who aided in the preparation of the manuscript. The colored drawings of gem crystals and cut stones reproduced in plates 13, 14, 16, 17, and 18 were the work of David P. Willoughby. The hand-tinted photograph of a kunzite crystal shown in plate 15 was donated by Waldemar T. Schaller. The aerial photographs shown in plates 25-28 were obtained by means of a special grant of funds from the California Institute of Technology. The manuscript was critically reviewed by Lincoln R. Page, John H. Eric, and Waldemar T. Schaller, who made numerous helpful suggestions.

PHYSICAL FEATURES

The Pala district is in northwestern San Diego County, about 45 miles north of San Diego and 80 miles southeast of Los Angeles. It lies 10 miles due east of Fallbrook and 17 miles due north of Escondido, and occupies a part of the San Luis Rey River Valley about midway between the Henshaw Reservoir and the river mouth at Oceanside (fig. 1). Like most of the other pegmatite districts in southern California, the Pala district is in the Peninsular Range province, which consists mainly of a series of mountain masses extending from about the latitude of Los Angeles southeastward into Baja California. This province is characterized by crystalline rocks, most of which are of igneous origin.

Most of the pegmatites discussed in this report are exposed on the crests and along the sides of several small mountain masses north and northeast of Pala, a mission village on the San Luis Rey River. The remainder of the district flanks the river valley on the south, and lies southeast of Pala. The main, or northern part of the district occupies an area of about 5 square miles. It lies along the southwestern base of the Agua Tibia-Palomar Mountain mass, and is about 5 miles beyond the southeastern end of the elongate Elsinore-Temecula-Pechanga Valley. Topographically it is characterized by steep and locally very irregular slopes in sharp contrast to the broad, alluvial floor and associated fans of the adjacent river valley.

The hills are circular to markedly elongate in plan, and show no uniform trend. They rise as much as 1500 feet above Pala, which itself is 410 feet above sea level, and the local relief in most parts of the district exceeds 800 feet. The principal eminences, listed in order from west to east, are Queen Mountain (1922 feet), Big Chief Mountain (1607 feet), Chief Mountain (1504 feet), Little Chief Mountain (1143 feet), Hiriart Mountain (1774 feet), Meadow Mountain (1927 feet), and Slice Mountain (1850 feet). The summit of the much larger Pala Mountain, in the southern part of the district, is 2026 feet above sea level. The major hills north and northeast of Pala are flanked by the alluviated canyons of such high-gradient streams as Pala Creek, Salmons Creek, McGee Creek, and Agua Tibia Creek, all of which drain southward and southwestward into the San Luis Rey River. To the northeast are the bold spurs and deep canyons of Agua Tibia Mountain.

Pala is served by the paved highway that extends from Oceanside to Henshaw Reservoir. This road connects with U. S. Highway 395, the Los Angeles-San Diego "Inland Route", 8 miles west of Pala, and with State Highway 79 at the south end of Henshaw Reservoir. Pala can be reached also from the north via the 9-mile Pala Canyon route, a winding paved road that connects with U. S. Highway 395 south of Temecula. The mine areas north and northeast of Pala are served by dirt roads. Some of the roads are no longer maintained and a few are impassable. Most of the mines can be reached by trail only.

Most of the district lies within the boundaries of the Pala Indian Reservation and the Mission Indian Reserve. The fertile valley bottom soils in the vicinity of Pala are tilled by Indian families for corn, alfalfa, and other field crops, and the Agua Tibia fan farther east supports the growth of large citrus orchards. Although most irrigated farms use water from wells, water from the San Luis Rey River and Agua Tibia Creek is used in some places. Some crops are grown also on a few scattered ranches in the highland areas. Vegetation there supports small scale cattle grazing and beekeeping.

The annual rainfall in the area is less than 20 inches, and there are few perennial streams. The Agua Tibia Mountain mass to the north, however, receives 25 to 40 inches of precipitation a year, and is the chief source of the ground water in the alluvial valleys near Pala. Where not under cultivation, these valleys support the growth of oak, cottonwood, and sycamore trees. In contrast, the hills on which deposits have been mined are covered with a heavy growth of chaparral interrupted only here and there by burned-over areas, and clusters of oak trees. On some north and east slopes the brush is so dense and tightly intergrown that it interferes seriously with the prospecting and geologic investigation of rock outcrops, which are abundant in most areas.

HISTORICAL SKETCH

Crystals of gem tourmaline were discovered in southern California by Henry Hamilton in June 1872. The occurrence, on the southeast slope of Thomas Mountain in the Coahuila Mountain district of Riverside County, comprised a few prismatic crystals of pink and green color. Several nearby deposits, discovered shortly thereafter, yielded a small output that included some excellent specimen and gem material. In 1898 commercial exploitation of the world-famous Himalaya pegmatite in the Mesa Grande

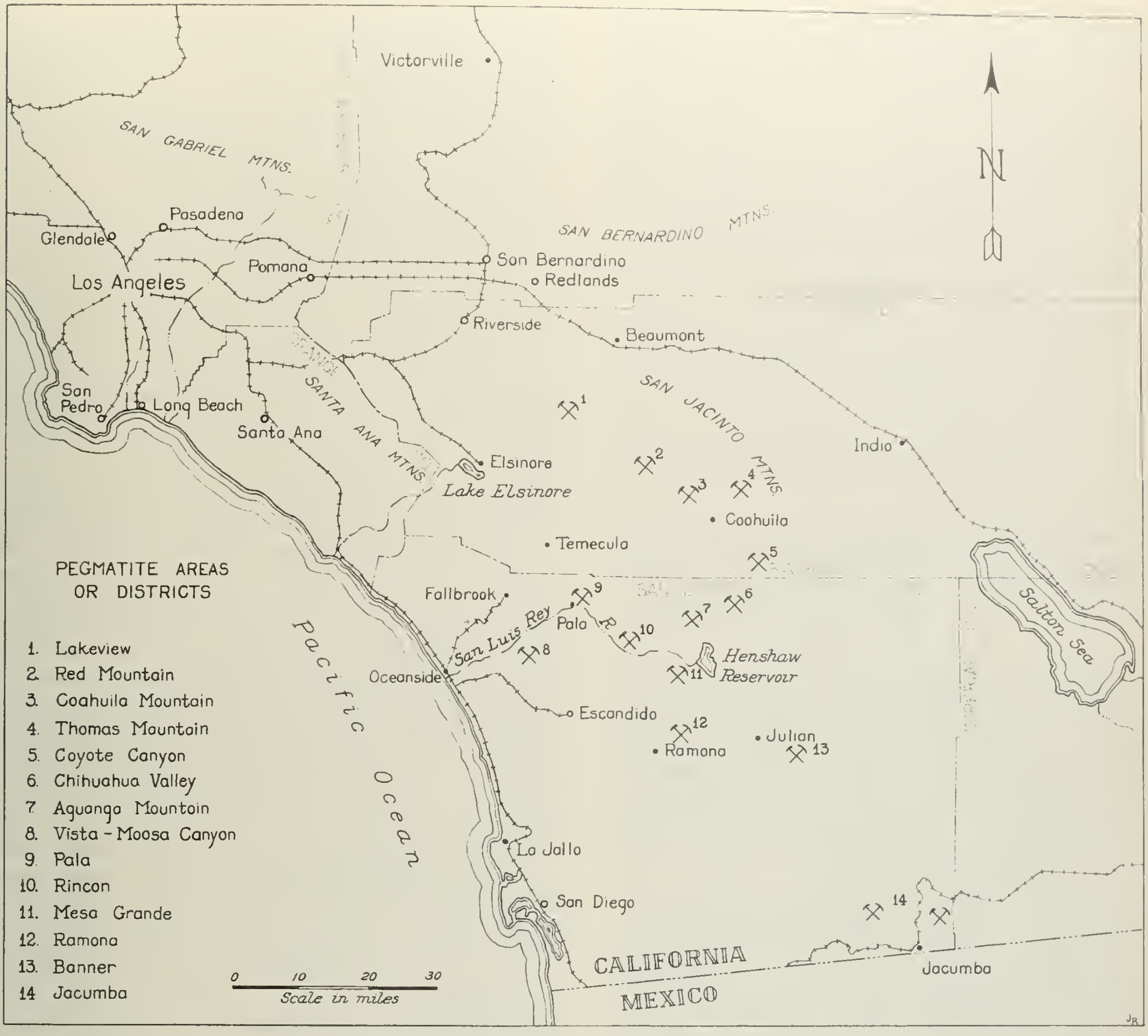

FIG. 1. Index map showing locations of principal pegmatite areas and districts in southern California.

district was begun, although as pointed out by Kunz,[8] this and other gem-bearing pegmatites in the area must have been known and worked by the local Indians for many years, as tourmaline crystals have been found in many Indian graves.

The first specific mention of tourmaline in the Pala district dates from 1892, when C. R. Orcutt announced the occurrence of pink tourmaline and lepidolite in the Stewart dike. Specimens of the fine-grained mica with individual prismatic crystals and radiating crystal clusters of rubellite had been known and described nearly ten years previously, but no precise information as to their geologic occurrence or geographic location had been recorded. The deposit is said to have been discovered by an Indian deer hunter. It was first worked by Henry McGee, an old prospector who had incorrectly interpreted the rubellite as an ore of quicksilver;[9] later it was briefly mined as a deposit of unusual marble by Don Tomas Alvarado, a local Spanish landowner. The economic potentialities of the pegmatite minerals were not recognized until the lepidolite in a specimen from a New York collection was identified by a German chemist who was familiar with lithia occurrences in Europe.

Most of the first lepidolite obtained from the Stewart deposit was sold as specimen material, but some was shipped to Germany for testing as a source of lithium, caesium, and rubidium. Development of the Stewart mine as a source of lepidolite stimulated a search for lithium deposits elsewhere in the district, and this search resulted in several discoveries of both lepidolite and gem minerals. Coarse crystals of gem-quality rubellite and other varieties of tourmaline were found in the Tourmaline King, Tourmaline Queen, and Pala Chief pegmatites, as well as in the central and northern parts of the Stewart dike. A little gem beryl and large quantities of clear crystallized quartz also were encountered.

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[8] Kunz, G. F., Gems, jewelers' materials, and ornamental stones of California: California Min. Bur. Bull. 37, pp. 23-24, 1905.

[9] Kunz, G. F., op cit., p. 124, 1905.

While doing assessment work during 1902 in the Katerina pegmatite, M. M. Sickler and his son, Frederick, penetrated a concentration of large quartz crystals in a matrix of unusual pinkish clay. Also in this clay were splinters and coarse, nodular to blade-like crystal fragments of a clear, colorless to straw-yellow and pale-lilac mineral that neither man could identify. Some of these pieces were similar to colorless fragments that had been picked up as float material on the nearby White Queen claim several years before. A series of similar discoveries was made on Chief Mountain, farther west, by Bernardo Hiriart and Pedro Feiletch, two Basque prospectors, and by Frank A. Salmons, who was to become one of the leading figures in the development of the district. Efforts to identify the mineral were unsuccessful until the Sicklers, in December, 1902, sent several specimens to Dr. G. F. Kunz, gem expert for Tiffany and Company in New York City, who recognized it as spodumene and announced its discovery.[10] About the same time, similar material furnished by F. A. Salmons was described in greater detail by Schaller.[11]

During the mining of these and other deposits of gem spodumene, tourmaline, and lepidolite in the Pala area, fine transparent quartz crystals and colorless, blue, golden, and pink to peach-colored crystals of beryl were recovered. Prospecting for gems was carried on vigorously from 1903 to 1914, and more than 50 deposits were mined. This was the golden era of activity in the district. Production declined sharply after 1914, as a result of dwindling markets and reduced prices, and never again reached the earlier levels. In 1914 the Tourmaline King mine was sold, and although the new owners spent many thousands of dollars in exploring all promising parts of the pegmatite, few marketable gems were recovered. During the 20's and 30's little more than assessment work was done in the largest mines, and the others were idle.

By 1940, the quantities of domestic tourmaline, kunzite, and pink beryl available on the market had become so small that prices began a distinct rise. This rise continued through the decade, and resulted in some revival of mining in the district. George Ashley of Pala purchased the claims on Hiriart Mountain from Fred M. Sickler in July, 1947, and subsequently sold three of these claims to Norman E. Dawson of San Marcos. Mr. Ashley reopened the Katerina mine, and recovered small quantities of excellent kunzite from inner parts of the pegmatite. The Fargo and White Queen mines, also on Hiriart Mountain, were worked in 1948 and 1949 by Mr. Dawson. Monta J. Moore of Pala, as representative of the F. A. Salmons estate, was planning to reopen the famous Tourmaline Queen and Pala Chief mines late in 1949.

Lepidolite mining in the Pala district centered about the Stewart dike, and small quantities of lithia mica were contributed from time to time by operators in the Tourmaline King, Tourmaline Queen, Pala Chief, Katerina, and Vanderburg mines.

GEOLOGY

General Features

Most of the Pala district is underlain by a series of intrusive rocks of late Mesozoic age which are part of the very large and complex southern California batholith of the Peninsular Range province.[12] This batholith comprises many separate intrusive units, or plutons, that range in exposed diameter from a few hundred feet to ten miles or more. In composition they range from gabbro to granite; representatives of the gabbro, tonalite, and granodiorite groups are especially widespread.

Metamorphic rocks of pre-batholith age are exposed in many parts of the province, but form a subordinate part of the crystalline complex. Post-batholithic sedimentary rocks cover the crystalline complex in the Elsinore-Temecula-Pechanga Valley, in many smaller valleys, and in a broad belt that fringes the coastline to the west.

The sedimentary and metamorphic rocks are much folded, the closeness and complexity of folding increasing with the age of the rocks. Both these and the rocks of the batholith are cut by numerous joints and faults, some of which have distinct topographic expression. The Elsinore fault zone, along which recent activity has been recognized, is the most impressive tectonic feature in the Pala area. It trends northwest, and bounds the district on the northeast.

The rocks exposed in the vicinity of Pala have been briefly described by several geologists in the course of studies of the pegmatites. In addition, more general descriptions of the geology have been published by Fairbanks,[13] Merrill,[14] Ellis,[15] Miller,[16] Larsen, and others. Additional investigations have been made in the nearby Cuyamaca area by Hudson,[17] Miller,[18] and Everhart;[19] the San Jacinto area by Fraser;[20] the Julian district by Donnelly[21] and Creasey;[22] the Perris area by Dudley;[23] and in a part of the Ramona quadrangle by Merriam.[24] The results of numerous studies of specific rock types

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[10] Kunz, G. F., On a new lilac colored spodumene, San Diego County, California: Science, new ser., vol. 18, p. 280, 1903.

[11] Schaller, W. T., Spodumene from San Diego County, California: California Univ. Dept. Geol. Sci., Bull., vol. 3, pp. 265-275, 1903.

[12] Larsen, E. S., The batholith of southern California: Science, new ser., vol. 93, pp. 442-443, 1941.

Larsen, E. S., Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America, Mem. 29, 182 pp., 1948.

Larsen, E. S., Time required for the crystallization of the great batholith of southern and Lower California: Am. Jour. Sci., vol. 243-A, pp. 399-416, 1945.

Larsen, E. S., and Keevil, N. B., Radioactivity of the rocks of the batholith of southern California: Geol. Soc. America Bull., vol. 58, p. 484, 1947.

[13] Fairbanks, H. W., Geology of San Diego County; also of portions of Orange and San Bernardino Counties: California Min. Bur., Rept. 11, pp. 76-120, 1893.

[14] Merrill, F. J. H., Geology and mineral resources of San Diego and Imperial Counties, California: California Min. Bur., Rept. 14, pp. 636-722, 1914.

[15] Ellis, A. J. and Lee, C. H., Geology and ground waters of the western part of San Diego County, California: U. S. Geol. Survey Water Supply Paper 446, pp. 50-76, 1919.

[16] Miller, W. J., Crystalline rocks of southern California: Geol. Soc. America Bull. vol. 57, pp. 476-488, 1946.

[17] Hudson, F. S., Geology of the Cuyamaca region of California with special reference to the origin of the nickeliferous pyrrhotite: California Univ., Dept. Geol. Sci., Bull., vol. 13, pp. 175-252, 1922.

[18] Miller, W. J., A geologic section across the southern Peninsular Range of California: California Jour. Mines and Geology, vol. 31, pp. 115-142, 1935.

[19] Everhart, D. M., Geology of the Cuyamaca Peak quadrangle, San Diego County, California: California Div. Mines Bull. 159, in press, 1951.

[20] Fraser, D. M., Geology of the San Jacinto quadrangle south of San Gorgonio pass, California: California Jour. Mines and Geology, vol. 27, pp. 494-540, 1931.

[21] Donnelly, M. G., Geology and mineral deposits of the Julian district, San Diego County, California: California Jour. Mines and Geology, vol. 30, pp. 331-370, 1934.

[22] Creasey, S. C., Geology and nickel mineralization of the Julian-Cuyamaca area, San Diego County, California: California Jour. Mines and Geology, vol. 42, pp. 15-29, 1946.

[23] Dudley, P. H., Geology of a portion of the Perris block, southern California: California Jour. Mines and Geology, vol. 31, pp. 487-506, 1935.

[24] Merriam, Richard, Igneous and metamorphic rocks of the southwestern part of the Ramona quadrangle, San Diego County, California: Geol. Soc. America Bull., vol. 57, pp. 223-260, 1946.

Table 1. Generalized section of rocks exposed in Pala district.

Age	General designation	Lithologic type
Quaternary	Surficial deposits	Landslide, talus, fan, and valley-fill deposits
Late Mesozoic (probably Cretaceous)	Rocks of the southern California batholith	Pegmatite Aplite Fine-grained granodiorite Coarse-grained granodiorite Felsic tonalite Mafic tonalite Gabbro and norite
Mesozoic and/or Paleozoic	Pre-batholithic crystalline rocks	Quartzite, schist, conglomerate, and rare marble

from the batholithic complex are also in the published record.[25]

Metamorphic Rocks

The metamorphic rocks of the Pala district are thin, elongate remnants of a once extensive sedimentary terrane. The remnants consist of quartzite, quartz conglomerate, meta-arkose, quartz-mica schist, quartz-mica-amphibole schist, and feldspathic amphibole schist, and are now transected and enclosed by younger igneous rocks.

These metamorphic rocks are most abundant in a discontinuous, broadly curving belt that extends around the west and north slopes of Queen Mountain, the south slopes of Carver and Big Chief Mountains, and the southwest slopes of the hills and ridges that lie north and east of Hiriart Mountain. Quartzite is dominant in the western part of this belt, schist in the eastern part.

The belt separates gabbroic rocks on the south from dominantly granodioritic rocks on the north. It tapers out at the southwest corner of Queen Mountain, and also at several places in the eastern part of the district. It is widest along the flanks and crest of the rugged ridge immediately east of Pala Canyon, where quartzite, quartz conglomerate, and associated metamorphic rocks have a maximum outcrop width of about 500 feet.

Bedding and schistosity in the quartzitic rocks are essentially parallel. On a larger scale, the trends of schistosity, of individual beds of quartzite, and of masses of schist and other metamorphic rocks also are parallel. Linear elements, mainly rows of biotite blades, amphibole needles, or stretched pebbles in conglomerate, are locally very well developed. Their plunges are generally very steep. The rocks are tightly folded on a small scale, as shown in many outcrops, but their broad structure appears to be simple. The main quartzite-schist belt is a thin septum or screen between plutons or pluton groups, and the other smaller masses of metamorphic rocks are roof pendants and inclusions within these plutons.

The metamorphic rock series in the Pala area is similar to parts of the Julian schist sequence in areas farther east, and all these pre-batholithic rocks may well be parts of the same general series. Even in the Pala area the quartzites, though dominant, are associated with much schist.

The age of the Julian schist (also called "basement complex," "schist complex," "Julian group," "Julian Schist Series," and "Bedford Canyon formation") is not accurately known, but this complex series has been correlated with fossiliferous rocks to the north and northeast, chiefly on the basis of lithology and geographic distribution. It has been suggested by Fairbanks,[26] Hudson,[27] and others, that the schist may correspond, at least in part, to the metamorphic sequence in the Santa Ana Mountains, which includes slate beds that contain Triassic fossils. That it may be in part of late Paleozoic age also seems possible, as pointed out by Hudson,[28] Miller,[29] and others. Rocks of both ages may well be represented in the series, which is assuredly older than the late Mesozoic rocks of the southern California batholith.

Igneous Rocks

Gabbroic Rocks

Gabbro, norite, and associated intrusive rocks of basic composition are very abundant in the vicinity of Pala, where they occur as composite plutons of circular to roughly elliptical plan. In general they are relatively resistant to erosion, and characteristically form prominent hills and ridges with smooth, regular slopes and thin mantles of dark reddish-brown soil. Examples of such eminences are Pala Mountain, Queen Mountain, Chief mountain, and Hiriart Mountain.

Individual rock types include medium- to coarse-grained gabbro and norite, olivine gabbro and norite, hornblende-rich gabbro and norite, hornblende-biotite gabbro and norite, and quartz-bearing gabbro and norite. All these types have been included under the general name San Marcos gabbro by Miller,[30] and in some areas to the southeast they have been designated as Cuyamaca basic intrusive by Hudson,[31] Donnelly,[32] and others.

The most common rock type in the Pala district is a dark-gray, medium-grained, equigranular, homogeneous olivine-hornblende-hypersthene gabbro. Its principal constituents, listed in order of decreasing abundance, are calcic plagioclase, hornblende, olivine, augite, and hypersthene. Accessory minerals include biotite, ilmenite, magnetite, pyrite, pyrrhotite, and spinel.

All but the most mafic or fine-grained gabbros and norites yield boulders with somewhat light-colored surfaces. These surfaces are strongly pitted, because of the

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[25] See, for example:

Kessler, H. H., and Hamilton, W. R., The orbicular gabbro of Dehesa, California: Am. Geologist, vol. 34, pp. 133-140, 1904.

Lawson, A. C., The orbicular gabbro at Dehesa, San Diego County, California: California Univ., Dept. Geol. Sci., Bull., vol. 3, pp. 383-396, 1904.

Schaller, W. T., Orbicular gabbro from Pala, San Diego County, California: U. S. Geol. Survey Bull. 490, pp. 58-59, 1911.

Miller, F. S., Anorthite from California: Am. Mineralogist, vol. 20, pp. 139-146, 1935.

Hurlbut, C. S., Dark inclusions in a tonalite of southern California: Am. Mineralogist, vol. 20, pp. 609-630, 1935.

Miller, F. S., The petrology of the San Marcos gabbro, southern California: Geol. Soc. America Bull., vol. 48, pp. 1397-1425, 1937.

Miller, F. S., Hornblendes and primary structures of the San Marcos gabbro, southern California: Geol. Soc. America Bull., vol. 49, pp. 1213-1232, 1938.

Osborn, E. F., Structural petrology of the Val Verde tonalite, southern California: Geol. Soc. America Bull., vol. 50, pp. 921-950, 1939.

Merriam, Richard, A southern California ring-dike: Am. Jour. Sci., vol. 239, pp. 365-371, 1941.

Merriam, Richard, Orbicular structures in aplite dikes near Ramona, California: Am. Jour. Sci., vol. 246, pp. 129-137, 1948.

[26] Fairbanks, H. W., op. cit., pp. 82, 87, 1893.

[27] Hudson, F. S., op. cit., pp. 188-190, 1922.

[28] Op. cit.

[29] Miller, W. J., op. cit., pp. 477-485, 1946.

[30] Miller, F. S., Petrology of the San Marcos gabbro, southern California: Geol. Soc. America Bull., vol. 48, pp. 1399-1400, 1937.

[31] Hudson, F. S., Geology of the Cuyamaca region of California, with special reference to the origin of the nickeliferous pyrrhotite: California Univ., Dept. Geol. Sci., Bull., vol. 13, pp. 193-207, 1922.

[32] Donnelly, M. G., Geology and mineral deposits of the Julian District, San Diego County, California: California Jour. Mines and Geology, vol. 30, pp. 341-342, 1934.

FIG. 2. Aerial view of the Pala district. Pala Mountain in foreground at left, Pala in valley beyond and at extreme left, and Elsinore-Temecula-Pechanga Valley in distance. At right are crest and spurs of Agua Tibia Mountain. View is toward the northwest. *Pacific Air Industries photo.*

relatively rapid weathering of plagioclase. On freshly broken surfaces, the plagioclase is greenish to bluish-gray, and gives a distinctive color to the rock.

In many places two or more rock types are interpenetrated in a complex way. The various facies of gabbroic rocks are combined as a single unit in plate 1, and are identified merely as ''gabbro'' on the detailed maps of pegmatite deposits.

The broad structure of the gabbroic masses is best shown by the fringing remnants of earlier quartzite and schist, which outline them on the west, north, and east (pl. 1). Their internal structure is much more complex, as most of them are composites of several rock types. Flow layering is well developed in some of the hornblendic rocks, but is confined to such small areas that it cannot be used effectively in deciphering the large-scale structures. Of even more local occurrence are nodular, orbicular, and auto-injection structures,[33] and also abundant pegmatitic masses of apparent segregation origin.

The gabbro, norite, and associated basic rocks contain inclusions of quartzite and schist, and appear as apophyses in larger masses of these rocks. Thus they are clearly younger than the metamorphic series, although they are the oldest of the plutonic rocks exposed in the Pala district.

Tonalite

At least two varieties of tonalite are present in the area. Both rocks are distinctly lighter in color than the gabbros and norites, and have feldspar grains that are generally white to light-gray in hand specimens. Both tonalites commonly form slopes covered by rounded boulders that range in diameter from 1 foot to more than 10 feet, in contrast to the smooth slopes underlain by gabbroic rocks.

One variety of the tonalite is a medium-to coarse-grained, moderately light-gray rock that contains scattered ovoid inclusions of gabbro, quartzite, and schist. It forms dikes and thick, tongue-like masses on Hiriart Mountain, and composes the two small, low hills immediately southeast of Queen Mountain (pl. 1). The other variety is fine-to medium-grained, medium to dark gray, and in most places is distinctly schistose. It is characterized by abundant discoid to elongate inclusions of darker, finer-grained rock, which are strung out parallel to the planar structure of the host rock. This finer-grained variety of tonalite composes most of Little Chief Mountain, and forms dikes and larger masses on some of the low hills southwest of McGee Flats and on the larger hills west of Pala. It also forms large, irregular dikes on the crest and slopes of Chief Mountain.

The relatively dark, fine-grained tonalite consists typically of andesine or labradorite, biotite, hornblende, quartz, augite, and minor hypersthene, with accessory magnetite, apatite, sphene, and zircon. The coarser-grained, lighter-colored tonalite consists of more sodic plagioclase (in the andesine-oligoclase range), biotite, hornblende, orthoclase, and rare augite and hypersthene. Accessory minerals are sphene, apatite, zircon, and magnetite.

The dikes and other masses of darker gray, finer-grained tonalite are distinctly younger than the enclosing gabbroic rocks, and are in sharp contact with them in most places. The trends of these contacts are closely reflected by the well-developed schistosity and streaked pattern of the platy inclusions that are characteristic of the tonalite. This rock is in contact with the coarser tonalite in only a few places, where the two types appear to merge. About a quarter of a mile south-southwest of the summit of Chief Mountain, however, the coarser type has formed apophyses in the finer-grained tonalite, and contains inclusions of this evidently earlier rock. Similar relations are exposed near the west end of a small quarry that lies on the north side of the highway immediately west of Pala.

On the basis of its texture, mineral composition, and general age relations, the finer-grained tonalite is assigned to the Bonsall, one of the most extensive rock types in the Peninsular Range province.[34] The less abundant, coarser type also may correspond to parts of the Bonsall, or it may be more closely allied to one of the other tonalites of Miller,[35] Larsen,[36] Merriam,[37] and others.

Granodiorite

Coarse-grained granodiorite underlies much of the northern part of the district, where it appears as the eastward and southeastward tapering prong of a very large intrusive mass (pl. 1). It is resistant to erosion, and forms rough, craggy mountains with boulder-strewn slopes that contrast with the relatively smooth and even slopes of the nearby gabbro mountains. The rock has been termed the Woodson Mountain granodiorite by Miller [38] and Larsen,[39] and is the most widespread granodiorite in the Peninsular Range batholith.

The rock is rather uniformly coarse-grained and light gray, with abundant phenocrysts of potash feldspar as much as half an inch in diameter. Its constituent minerals, listed in order of decreasing abundance, are oligoclase, quartz, orthoclase and microcline, biotite, muscovite, and hornblende, with accessory apatite, magnetite, sphene, and zircon. The mafic minerals rarely amount to more than 8 percent of the total, and in most places are much less abundant.

Typically the large granodiorite pluton is massive, but has well-developed schistosity and foliation along its borders, generally in a belt not more than 1200 feet wide. Although very irregular in detail, these planar features are essentially parallel, and are oriented in crude conformity with the adjacent wallrock contacts.

A coarse-grained migmatitic rock is exposed on the west side of Queen Mountain, where it forms many small cliffs on both walls of a narrow canyon. It consists of irregularly contorted biotite-bearing layers $\frac{1}{8}$ to 1 inch thick, separated by biotite-free layers of similar thickness. It appears to be a gneissic hybrid rock developed from a

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[33] Schaller, W. T., Orbicular gabbro from Pala, San Diego County, California: U. S. Geol. Survey Bull. 490, pp. 58-59, 1911.
Miller, F. S., Hornblendes and primary structures of the San Marcos gabbro: Geol. Soc. America Bull., vol. 49, pp. 1220-1230, 1938.

[34] Hurlbut, C. S., Dark inclusions in a tonalite of southern California: Am. Mineralogist, vol. 20, pp. 609-630, 1935.
Merriam, Richard, Igneous and metamorphic rocks of the southwestern part of the Ramona quadrangle, San Diego County, California: Geol. Soc. America Bull., vol. 57, pp. 243-246, 1946.
Larsen, E. S., and Keevil, N. B., Radioactivity of the rocks of the batholith of southern California: Geol. Soc. America Bull., vol. 58, p. 488, 1947.

[35] Miller, F. S., op. cit., pp. 1408-1409, 1937.

[36] Larsen, E. S., Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America Mem. 29, pp. 53-57, 70-76, 1948.
Larsen, E. S., and Keevil, N. B., op. cit., 1947.

[37] Merriam, Richard, op. cit., pp. 240-243, 247-250, 1946.

[38] Miller, F. S., op. cit., p. 1399, 1937.

[39] Larsen, E. S., op. cit., p. 76, 1948.
Larsen, E. S., and Keevil, N. B., op. cit., p. 489, 1947.

schistose terrane, but its over-all composition is only slightly different from that of the flanking granodiorite.

Inclusions of schist, quartzite, tonalite, and gabbroic rocks are widespread, but are nearly everywhere less abundant than those in the tonalites. Where the granodiorite is schistose, the inclusions are oriented in essential conformity with this structure, but elsewhere they show no consistent orientation. The relative ages of the rocks are further demonstrated by dikes of granodiorite that locally cut the tonalites and gabbroic rocks, and by a thick intrusive prong of granodiorite on the southeast corner of Hiriart Mountain (pl. 1). A contact zone between granodiorite and gabbro is almost continuously exposed on the north wall of Castro Canyon, due north of the summit of Hiriart Mountain.

Another variety of felsic granodiorite, well foliated and locally very schistose, is much finer-grained than the typical Woodson Mountain granodiorite. In a general way it forms the outer part of a thin, "two-ply" envelope around the large gabbroic mass north and northeast of Pala, and is separated from the gabbro in most places by the thin screen of quartzite and schist previously described. The outcrop belt of this fine-grained granodiorite ranges in width from a few feet to 700 feet or more. It is remarkably continuous, but pinches out in a few places. The rock is very resistant, and appears as large boulders and craggy masses. From a distance it cannot be distinguished from the typical coarse-grained Woodson Mountain granodiorite that bounds it on the west, north, and east.

The fine-grained granodiorite is composed of quartz, microcline and orthoclase, oligoclase, biotite, muscovite, and scattered accessory minerals. The quartz and potash feldspar are more abundant than in the typical Woodson Mountain granodiorite. Numerous inclusions and wispy remnants of quartzite and other metamorphic rocks are present in many areas, and in places there are all gradations between these pre-batholithic rocks and typical granodiorite.

The relations between the fine-grained granodiorite and the typical Woodson Mountain are exceedingly complex in detail. In most places the two rocks are thinly interfingered, with septa and inclusions ranging in length from a foot to several hundred feet and in width from an inch or less to as much as a hundred feet. Most of them are too small to be shown on the geologic map (pl. 1). The rocks grade into one another in detail, and in only a few places are their age relations determinable. The fine-grained type occurs in the coarser rock as irregular dikes with vague boundaries, and appears to be the younger of the two. It was formed probably in part by migmatitization and granitization of schist, quartzite, and associated rocks, and in part by intrusion of granodioritic magma along the contact zone between these metamorphic rocks and the Woodson Mountain granodiorite. Its foliation and schistosity are interpreted as a relict structure in most places, and as a flow structure in others.[40]

Dike Rocks

Masses of fine-grained lamprophyre cut the gabbroic rocks in many places. They are most abundant in the olivine gabbros and norites, in which they form both thin, irregular lenses and stringers, and swarms of closely spaced subparallel dikes. These masses are especially common on the southeastern part of Queen Mountain, where they range in thickness from less than an inch to about a foot. Most of them are traceable for strike distances of more than 30 feet. The constituent minerals include plagioclase in the bytownite-anorthite range, hornblende, and magnetite, with local ilmenite, hypersthene, and augite. The bulk composition of a given dike is generally little different from that of the adjacent country rock, and such dikes probably were derived from sources within the gabbroic plutons themselves.

Aplitic dikes of granodioritic composition are exposed on the west side of Chief Mountain, on a low hill northwest of Hiriart Mountain, and on the ridge immediately west of Pala (pl. 1). They are more resistant to weathering than the enclosing rocks, and consequently stand out as riblike masses or as rows of elongate boulders. They are rarely more than 6 feet thick, but are 100 feet to as much as half a mile long. They transect all the other rocks described in the foregoing paragraphs, but are themselves cut by younger dikes of pegmatite.

Most of the aplitic dikes consist of quartz, potash feldspar, oligoclase, muscovite, biotite, and scattered magnetite, with rare garnet, zircon, tourmaline, and other accessory minerals. The rocks are light-gray to buff, fine-grained, and thinly schistose. They are even-grained in some places, but elsewhere they grade inward from aplitic borders to pegmatitic centers. In a few places they closely resemble the younger pegmatite dikes, but grade along the strike into typical aplitic rocks that are cut by irregular veinlike masses of pegmatite and quartz.

Pegmatite dikes are abundant in the gabbroic rocks, and occur also in the older metamorphic rocks and in the tonalite and granodiorite members of the batholithic sequence. They transect the tonalite and granodiorite dikes on Chief Mountain, and appear to be among the youngest rocks exposed in the district. These pegmatite dikes range in thickness from less than an inch to nearly 100 feet, with an average thickness of slightly less than 10 feet. Most of them trend north and dip westward at small to moderate angles. They are described in greater detail farther on.

Other Rocks

Post-batholithic rocks in the Pala district comprise coarse-grained fan and valley-fill deposits of Quaternary age. The oldest unit, a series of well-bedded, poorly consolidated arkoses and pebble-to-boulder conglomerates, has been termed the Pala conglomerate by Ellis.[41] It appears to be a complex fan deposit that was derived principally from Agua Tibia Mountain and other high areas to the north. It underlies the broad fan surface that extends westward and southward from the mouth of Agua Tibia Canyon, and is well exposed in several highway cuts and on a long, steep cliff cut by the San Luis Rey River. The same rock forms the old fans immediately north and northeast of Pala, and also a 5- to 40-foot capping over crystalline rocks on McGee Flats. Its thickness at several places near Pala is at least 250 feet.

The sedimentary structures in the formation are typical of fan deposits, and include well-defined but lenticular bedding and irregular alternations of coarse-

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[40] For a brief discussion of these features, see: Jahns, R. H., Discussion in Origin of granite: Geol. Soc. America, Mem. 28, pp. 94-95, 1948.

[41] Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, California: U. S. Geol. Survey Water-Supply Paper 446, p. 70, 1919.

grained and relatively fine-grained debris. Some parts of the formation, in contrast, are composed wholly of thick, boulder-rich beds. An unusually fine-grained facies is exposed along the highway near the southeastern corner of the area shown in plate 1, and still finer grained deposits have been penetrated in wells beneath the valley bottom farther southeast. These deposits, which contain abundant plant material, may well have been laid down in a short-lived lake that was formed behind the large, rapidly constructed Agua Tibia fan.

The Pala conglomerate contains scattered vertebrate remains, chiefly Pleistocene horses and elephants. The formation is probably correlative, either wholly or in part, with the Pleistocene arkoses of the Elsinore-Temecula-Pechanga Valley to the north.

The valleys of all the principal streams have floors of Recent alluvium. It forms the broad flat at Pala, and also the somewhat narrower river-bottom flats to the east. Some alluvium is present in the narrow ravines and broad washes that have been cut into the old fans of Pala conglomerate, and in many areas of low topographic relief the two units are not easily distinguished. The alluvium consists mainly of sand, gravel, and interbedded silt, but well logs indicate that there are concentrations of large boulders in the lower part.

Accumulations of slope debris are present on most of the mountains, especially in areas of locally extreme relief. Weathered gabbro has formed small landslides on the south slopes of Queen Mountain and the north slopes of Pala Mountain; larger landslides involving gabbro and pegmatite on Hiriart Mountain are characterized by concentrations of pegmatite boulders that are as much as 15 feet in diameter. Some of the boulders have been prospected for pegmatite minerals.

Structure

Most of the crystalline rocks are marked by distinct planar structures. These structures include mineral layering, oriented inclusions of discoid or tabular form, and oriented plates or tablets of biotite, hornblende, feldspar, and other minerals. Bedding is distinct in many of the metamorphic rocks. Of local prominence are linear elements, generally with steep plunges, that are formed by the axes of "stretched" pebbles in beds of conglomerate, the axes of elongate mineral grains, intersections of bedding and schistosity, and lines of biotite flakes, hornblende needles, and other mineral grains.

The planar and linear elements are only locally well developed in the gabbroic rocks, and show no general or consistent pattern. In contrast, the foliation and schistosity of the tonalite and granodiorite rock masses are typically parallel to their contacts, and appear to have been mainly the result of flowage during intrusion. The planar structure of the fine-grained granodiorite is an exception, in that it is probably in part a relict feature preserved from older rocks at whose expense much of the granodiorite was developed. Planar elements which are very abundant in the pegmatite dikes are described in a later section.

Much of the schist-quartzite series seems to have a very simple structure, even though the beds are on edge in most places. In detail, however, some beds are closely folded, crinkled, or otherwise distorted. The remnants of these rocks are so small that it has not been possible to determine the general attitude and pattern of such folds.

Ptygmatic folds are locally abundant in the gabbroic and granodioritic rocks, and many of them are outlined by quartz or by thin aplitic masses. These flexures vary in orientation and degree of development from one place to another, and many appear to be related to nearby boundaries of the enclosing plutons. The Woodson Mountain granodiorite exposed on the southwestern face and southeastern end of Slice Mountain is much sheared on a small scale, and in many places has been converted to a flaser gneiss. This severely sheared rock forms a southeastward tapering prong between two masses of gabbroic rocks.

The crystalline rocks are cut by many joints, most of which form well-developed sets. Some of the fractures are spaced so closely that the host rock has a sheeted appearance, but most are at least ten feet apart. In few places, however, are the rocks free from joints for distances of more than 50 feet. Joint structure is best shown in the granodiorites, because parts of them have been eroded leaving large residual boulders distributed in regular patterns.

Two general classes of joints are present in most areas. One ordinarily comprises two sets that dip steeply and differ in strike by 60 degrees or more. They are very prominent in the granodiorite along the western and northern edges of the district, where one set is subparallel to the contact zone between granodiorite and older rocks, and the other is nearly normal to it. The other class of joints bears no systematic relation to the shapes or attitudes of the plutons, but instead appears to be related to some broader feature. Typical of this class are fractures that trend north and dip gently to moderately west in the gabbro and associated rocks. They transect contacts between different crystalline rocks, and are remarkably uniform in attitude. They are of considerable interest in the study of the Pala pegmatites, as it is along many of these joints that the pegmatite dikes were emplaced.

Perhaps the outstanding tectonic feature in the Pala region is the Elsinore fault, which bounds the pegmatite district on the northeast. It is actually a fault zone, half a mile to more than a mile wide, that comprises many subparallel breaks, zones of gouge and breccia, and horses of relatively unbroken rock. It has a profound effect upon local topography, appearing as a gentle elongate depression. The southwesternmost fault of the Elsinore zone lies along the edge of McGee Flats and traverses Meadow Mountain, and the northeasternmost fault lies beyond the mapped area shown in plate 1. These and other breaks trend northwest and dip very steeply. These faults have had several thousand feet of movement, perhaps, but neither the magnitude nor direction of movement is determinable from evidence in or near the Pala district. That the fault zone is still active is demonstrated by the many earthquake epicenters along its trace.

Less significant faults are exposed in several parts of the pegmatite area. One of them crosses the saddle between Chief and Little Chief Mountains, and separates gabbro on the north from tonalite on the south. It is traceable for at least a mile west of Pala, and evidently has a moderately large displacement. Numerous minor faults, which have east to northeast trends and steep dips, cut and offset pegmatites on the east side of Queen Mountain, and a few similar faults appear elsewhere in the district. None of them has displacements that exceed 50 feet.

Table 2. Principal pegmatite dikes, mines, and prospects in main part of Pala district.

Mountain [a]	Pegmatite dike or dike group [a]	Mines and/or prospects [b]	No. on plate 2	Principal output [c]
Queen Mountain	West Canyon	West Canyon (Freak) prospect	1	------------
	Maud	Maud prospects	2	------------
	Happy Hooligan	Happy Hooligan prospect	3	------------
	Tourmaline King	Tourmaline King (Wilke, Schuyler) mine	4	Tourmaline, quartz
		Ed Fletcher mine	5	Tourmaline, quartz
	White Cloud	White Cloud (Buster Brown) mine	6	Tourmaline, quartz
	Emerald	Emerald (Upper Queen) prospects	7	------------
	Tourmaline Queen	Tourmaline Queen mine	8	Tourmaline, quartz
		Queen Extension prospects	9	------------
		Pala View (Sholder-Trotter) mine	10	Tourmaline, quartz
	Mission	Mission mine	11	Tourmaline, quartz
	Pala King	Pala King (Spring Bank, Wedge) prospect	12	------------
	Stewart	North Star mine	13	Tourmaline, quartz
		Gem Star (Loughbaugh) mine	14	Tourmaline, quartz
		Stewart mine	15	Lepidolite, tourmaline
		Alvarado mine	16	Lepidolite, tourmaline
	Stewart Extension	Stewart Extension prospect	17	------------
Queen Mountain	Homestake	Homestake prospect	18	------------
	Douglass	North Douglass prospect	19	------------
		Douglass Extension prospect	20	------------
		Douglass mine	21	Tourmaline, quartz
		Pasture prospect	22	------------
		Pala Douglass mine	23	Tourmaline, quartz
Chief Mountain	Salmons View	Upper Salmons View prospect	24	------------
		Lower Salmons View prospect	25	------------
		Redlands King prospect	26	------------
	Blanket	Lower Blanket prospects	27	------------
		Upper Blanket prospects	28	------------
	Hazel W.	Hazel W. prospect	29	------------
Chief Mountain	West Chief	Canyon King prospect	30	------------
		West Knickerbocker prospect	31	------------
		Margarita mine	32	Beryl, tourmaline, quartz
		Crystal King prospects	33	------------
		Olla prospect	34	------------
		Butterfly prospect	35	------------
		Chief Extension prospects	36	------------
	Pala Chief	Pala Chief mine	37	Spodumene, tourmaline, beryl, quartz
		Verdant View (Anita) prospect	38	------------
	Chief Ridge	Chief Ridge prospects	39	------------
		East Knickerbocker prospect	40	------------
	Ocean View	Meadow prospects	41	------------
		Poison Oak prospects	42	------------
		Ocean View mine	43	Beryl, quartz
		Redwing (Redlands) prospects	44	------------
		Jackpot Tunnel (Butterfly) prospect	45	------------
	North End	North End prospects	46	------------
	Goddess	Goddess prospect	47	------------
	Snipe	Snipe prospect	48	------------
Little Chief Mountain	Big Slope	Big Slope prospect	49	------------
	Little Chief	Little Chief prospects	50	------------
	Cliff	Cliff prospects	51	------------
Hiriart Mountain	Anita	Chaparral prospects	52	------------
		Anita mine	53	Beryl, spodumene, quartz
		Spar Cut prospect	54	------------
Hiriart Mountain	Snake Den	Snake Den prospects	55	------------
	Center Drive	Center Drive prospect	56	------------
		Upper Katerina prospect	57	------------
	Senpe	Senpe (Sempa) mine	58	Beryl, lepidolite, quartz, tourmaline
		El Lobo prospects	59	------------
	White King	Pluto prospect	60	------------
		White King prospect	61	------------
	White Queen	White Queen mine	62	Spodumene, beryl, quartz
	Spar Pocket	Spar Pocket mine	63	Beryl, quartz
		San Pedro mine	64	Beryl, spodumene, quartz, tourmaline

Footnotes appear on page 15.

Table 2—Continued

Mountain [a]	Pegmatite dike or dike group [a]	Mines and/or prospects [b]	No. on plate 2	Principal output [c]
	Vanderburg-Katerina	Buttercup prospects	65	------------
		Vanderburg, (Naylor-Vanderburg, Sickler) mine	66	Spodumene, beryl, quartz, tourmaline
		Katerina (Ashley, Catherina, Katrina) mine	67	Spodumene, lepidolite, beryl, quartz, tourmaline
	Landslides from Vanderburg-Katerina dike group	Hiriart prospects	68	------------
		Hiriart mine	69	Spodumene, quartz
	Fargo	Fargo mine	70	Tourmaline, quartz
Hiriart Mountain	El Molino	Canyon prospect	71	------ ------
		Naylor mine	72	Tourmaline, quartz
		Tizmo prospect	73	------------
		El Molino mine	74	Beryl, quartz

[a] Listed from west to east.

[b] Listed from north to south, within each dike or dike group.

[c] Does not include material obtained by mineral collectors. Principal output of minerals other than lepidolite is gem and specimen material.

PEGMATITES

Distribution and Occurrence

The pegmatites in the Pala district occur in a curving belt that occupies an area of about 13 square miles. The belt extends from Pala Canyon south-southeastward to the southern base of Pala Mountain, and within it are exposed at least 400 pegmatite dikes. Other pegmatites are scattered through the surrounding area. Within the district, most of the deposits of known commercial interest lie north and northeast of Pala, on the slopes and crests of Queen Mountain, Chief Mountain, Little Chief Mountain, and Hiriart Mountain. These mountains and most of the pegmatites exposed thereon are shown on plate 2.

The pegmatites on Queen Mountain, westernmost and largest of the four mountains, are best known as commercial sources of lithium minerals, gem tourmaline, and quartz crystals. One deposit, the Stewart, has yielded more than 20,000 tons of lepidolite, some amblygonite and other lithium minerals, bismuth minerals, and a remarkable suite of phosphate minerals. Another, the Tourmaline Queen, has been the leading source of pink, green, and blue tourmaline in the district. Three pegmatite dikes, the Tourmaline King, Tourmaline Queen, and Stewart, have been extensively mined, and many others have been prospected or mined on a small scale. Most of these dikes are listed in table 2.

The Pala Chief mine, on Chief Mountain, has been the world's greatest source of gem spodumene. In addition it has yielded gem beryl and some gem tourmaline. These minerals have been recovered also in several prospects and small mines elsewhere on this hill, where the number of pegmatite dikes is considerably greater than on Queen Mountain to the west. Many pegmatites are exposed also on Little Chief Mountain to the south, but no mining and very little prospecting have been done there.

Pegmatite dikes are also closely spaced on Hiriart Mountain, on whose slopes they appear as well-defined riblike projections. Gem spodumene and beryl, quartz crystals, lepidolite, and some green tourmaline of gem quality have constituted the commercial output from the pegmatites on this mountain. Other lithium minerals, and several species of columbium-tantalum, bismuth, and phosphate minerals occur in the Katerina-Vanderburg dike group. The pegmatites most extensively worked include the Senpe, San Pedro, Katerina-Vanderburg, and El Molino (pl. 2), and there are at least 70 prospect openings in other dikes on the mountain.

A few outlying pegmatites are on the rugged hills immediately north of those described above. Most of them are small, and few are traceable for strike distances of more than 200 feet. The only dikes with marked continuity are exposed on the low hills north of Hiriart Mountain and immediately east of Chief Mountain. Even these dikes, however, do not appear to contain more than traces of lithium or gem minerals.

Many pegmatites occur on Pala Mountain, especially on its southwestern and eastern slopes. Some of them are shown in plates 1 and 2. Several contain quartz crystals and massive rose-colored quartz, and both tourmaline and beryl have been reported. Very little commercial production has been obtained from any of these dikes.

With only a few exceptions, the pegmatites are restricted to areas underlain by gabbroic rocks. This generalization applies particularly to pegmatites that contain deposits of commercial interest. The pegmatite areas coincide with the outcrop belt of one, or possibly two large plutons of gabbroic rocks, which in general are bounded on the north and east by granodiorite and metasedimentary rocks, and on the south and west by tonalite. Other, nearby intrusive masses of gabbro, though apparently similar in petrology and structure, contain very few pegmatites.

The intimate relation between pegmatite and gabbroic rocks is not ascribable to the relative age of these gabbroic rocks, but appears instead to be a reflection of some preferred structural feature in the gabbros and norites. The metasedimentary rocks of the pre-batholithic series, for example, antedate even the gabbro, and yet they are hosts to very few pegmatites. Moreover, the pegmatities are younger than the Bonsall tonalite, as they cut that rock on Little Chief Mountain and transect tonalite dikes in many other places (pl. 1). That they are also younger than the Woodson Mountain granodiorite is shown by their occurrence in a large mass of that rock on the southeastern part of Hiriart Mountain, the south edge of Carver Mountain, and at several other localities. They even cut across dikes of fine-grained granodiorite that are younger than the typical Woodson Mountain granodiorite.

Most of the pegmatites are well exposed, despite the thick cover of vegetation in much of the area. They are more resistant to erosion than most of the country rock, and thus typically form low knobs and rib-like protuberances on the hillsides. Such series of projecting outcrops are especially prominent on the east slopes of Little Chief and Hiriart Mountains. The pegmatite minerals are little altered by weathering, although much near-surface pegmatite is severely broken and otherwise mechanically disturbed. This disturbance is particularly common in exposures on and immediately below old erosion surfaces along the southwestern side of Queen Mountain and the west side of Pala Mountain. The adjacent gabbro is partly decomposed to depths of at least 30 feet in many places.

Excellent sections of most of the pegmatites may be seen where the dikes crop out on northeast, east, and southeast slopes, and in such places their structure and mineralogy can be observed. Studies in three dimensions are possible where the slopes are cut by narrow, steep-sided ravines, or where there are accessible mine workings.

General Structural Features

Form, Size, and Attitude

The pegmatites are strikingly uniform in shape. Nearly all are markedly tabular masses, and have gentle to moderate westerly dips. They range from stringers less than an inch thick to large dikes with bulges nearly 100 feet in maximum thickness. Most dikes of commercial interest are 5 to 25 feet thick, with an average thickness of slightly less than 10 feet. Most of them also are continuous, and can be traced along their strike for distances of half a mile or more. Most dikes that are thicker than 3 feet appear to be more than 400 feet long, and even the thinnest stringers are remarkably persistent.

A general uniformity in attitude is characteristic. The dikes range in strike from north-northwest to north-northeast, but most of them trend within a few degrees of due north. They dip westward at angles ranging from 5 to 60 degrees, but the dips of nearly all lie within the range of 10 to 35 degrees. The average value is about 20 degrees.

Two general types of irregularities in attitude, distinguished by a considerable difference in scale, are widespread in the area. The walls of some dikes are marked by numerous septa and tabular inclusions of country rock, most of which are less than 6 feet in maximum dimension. Other wallrock contacts are serrate on a small scale, with the amplitude of the irregularities rarely greater than half an inch. Most of the contacts, however, are remarkably regular in detail.

In contrast to their detailed regularity, nearly all the pegmatite dikes bend broadly in both strike and dip. Such variations are confined to a small range of attitudes, and generally form gentle rolls and terracelike features. These features are 20 feet to 600 feet or more wide, and 40 feet to more than 1,000 feet long. The axes of some are parallel to the strike of the pegmatite, and hence they appear as broad, gentle steps on the dike. Such essentially horizontal benches are most common on the west knob of Hiriart Mountain, where several pegmatites flatten in dip by as much as 40 degrees. Some of these structural terraces are 500 feet to 800 feet wide, and extend for distances of more than 1,500 feet along the strike of the pegmatite dikes. Similar features occur elsewhere in the district, but in general are much smaller.

The axes of other rolls are inclined, so that the simple form of the west-sloping dikes is complicated by broad corrugations. These axes plunge directly down the dip, or very nearly so. Such rolls are best exposed on the west slopes of Chief and Little Chief Mountains, where there are several broad dip slopes of pegmatite. The gabbroic wallrock is exposed as elongate but irregular patches where the crests of the rolls have been breached by erosion, or where the rock is preserved as hanging-wall remnants along the troughs of adjacent rolls. Both the plunging rolls and the terracelike features may have been partly responsible for the localization of commercially desirable minerals in certain parts of the pegmatite dikes.

Some of the major pegmatites, like the Tourmaline Queen, Stewart, and Douglass on Queen Mountain, are essentially isolated. Little or no pegmatite occurs in the nearby country rock, even as minor lenses or stringers. Other pegmatites form swarms of subparallel dikes that are separated by only a few feet or a few tens of feet of country rock. Such dike groups are widespread throughout the north-central and northeastern parts of the district.

An exceptional exposure of parallel dikes is on the southeastern face of Little Chief Mountain. Sub-parallel dikes are also exposed on Hiriart Mountain, but these dikes commonly branch out and converge, as traced along their strike. Markedly anastomosing patterns appear locally, but a general parallelism remains the most consistent feature.Three-dimensional exposures provided by canyons and by mine workings indicate that many of the pegmatites branch out or join one another in a down-dip direction. Many of those that are very close together converge to form thick composite dikes. Although such juxtaposed dikes crop out as single tabular masses of pegmatite, they commonly retain their individual identities, as shown by their internal structure and by the slivers and thin plates of country rock between some of them.

The dikes characteristically taper at their ends, forming thick stubs or thin, elongate prongs in the country rock. Some terminations are less simple, ranging from forked tongues to complex groups of pegmatite stringers. Locally these stringers form stockworks, especially where the country rock is quartzite or schist. In general the ends of the thickest dikes are most complex. They characteristically form series of subparallel septa and lenses along well-defined horizons in the country rock. This feature is shown in several parts of the underground workings at the Tourmaline King mine.

Relations to Wall-rock Structure

The pegmatites are not systematically related to the truly primary structural features in the enclosing rocks. Their general attitude, for example, is wholly independent of foliation, schistosity, and lineation in the plutonic and pre-batholithic rocks, and neither their form nor their size appears to be a function of such features in the igneous country rocks. The few pegmatites in the least quartzitic parts of the metamorphic series do reflect changes in structure and lithology of the wall rocks. They pinch and swell more than the other dikes, and commonly are distinguished by bulges and irregular protuberances where they cross the less competent layers of the wall rock. In general, however, the pegmatites in the quartzitic, or dominant part of the Julian sequence exposed in the Pala district, are little different in form and structure from those in the nearby batholithic rocks.

The striking uniformity in shape and attitude of the pegmatite dikes seems best attributable to their emplacement along a well-developed set of fractures. These fractures are present throughout the Pala district, and occur also in adjacent areas and in adjacent pegmatite districts.

Fig. 3. Aerial view of northern part of Pala district, showing contrast between the smooth slopes of Queen Mountain, Hiriart Mountain, and other hills underlain by gabbroic rocks and the adjacent more bouldery slopes underlain by granodiorite. View is toward the west-northwest. QM, Queen Mountain; CM, Chief Mountain; LCM, Little Chief Mountain; HM, Hiriart Mountain; SM, Slice Mountain; MF, McGee Flats; WC, White Cloud mine; TQ, Tourmaline Queen mine; S, Stewart mine; GS, Gem Star mine; K, Katerina mine; V, Vanderburg mine; EM, El Molino mine; G, Gabbro quarry. *Pacific Air Industries photo.*

In most places they do not contain pegmatite dikes, although of course they are most conspicuous where pegmatites have been injected along them. They are not related to individual plutons or other masses of country rock, but instead appear to have been superimposed uniformly upon groups of these masses and upon all earlier structural features within the masses. The fractures transect contacts between major rock units, and vary little in general attitude over areas of several square miles. They appear to be most abundant and closely spaced in the gabbroic rocks.

The origin of the pegmatite-controlling fractures is not clear. Attempts have been made to correlate them with the Elsinore fault and other major structural breaks in the region, but without success. They cannot be satisfactorily related to such faults in terms of abundance or trends in attitude, nor can they be well explained as fillings of gash or shear fractures in terms of known movements along a given fault. Finally, the pegmatites themselves, which fill some of the fractures, antedate much if not all of the fault displacement.

The fractures and pegmatites are almost certainly pre-Tertiary in age, but are distinctly younger than the individual units of batholithic rocks in which they occur. Perhaps the fractures are purely tensional features, developed by an almost regional subsidence during the end stages of cooling in the southern California batholith. They may well have been tilted westward since their formation, as the entire Peninsular Range province is thought to have been tilted in this direction to various degrees during middle and late Tertiary time.

Most irregularities in the pegmatite dikes are attributable to irregularities in the pattern of host fractures. In general, the branching pegmatites appear to have been emplaced along branching, subparallel fractures, even though some pegmatites do not follow these fractures in detail. Some bulges in the dikes probably have a similar origin, but others evidently were developed along intersections with different sets of fractures. The origin of still others is not clear. The structural terraces and rolls previously described appear to be direct reflections of variations in attitude of the fractures.

Principal Types of Pegmatite

Graphic Granite

Graphic granite forms the most widespread rock type in the Pala pegmatites. Typically it consists of large crystals of perthitic microcline, in which many spindlelike and rodlike anhedral grains of quartz lie essentially parallel to one another. Most of this rock is easily recognized in the field because of the quartz rods, although some varieties are so fine grained and dense appearing that at first they may be mistaken for other types of fine-grained pegmatite.

The graphic granite is ordinarily resistant to erosion, and forms bold, somewhat rounded outcrops. Together with massive quartz, it forms the best-exposed parts of the pegmatite dikes. In general it occurs along and near the hanging-wall parts of these dikes, but is by no means restricted to them.

The host crystals of perthite are white, gray, and tan, and the deep-flesh and reddish colors common in other pegmatite districts are rare here. The crystals are anhedral to euhedral; most are subhedral. They yield broad fairly straight cleavage surfaces 2 inches to more than 8 feet in diameter, with an average diameter of less than a foot. The microcline encloses typical blebs and tablets of albite, which in general are less than 1 millimeter thick. They range considerably in size, however, and the largest ordinarily are in the coarsest crystals of potash feldspar.

The quartz rods in the graphic granite that has the most regular structure are characteristically many times as long as they are thick. They range from about half an inch to 14 inches in maximum dimension, and have cross sections ranging from slightly less than $\frac{1}{16}$ inch to nearly an inch in diameter. Some of them are truly rodlike, with triangular to subrounded sections. Others are markedly platy, and still others have V- or L-shaped sections. Many are uniform in the direction of their elongation, but others bulge in the middle and taper near their ends. Some are closely spaced, and even touch one another, but most of them are at least as far apart as their own thicknesses. They are therefore separate masses, rather than elements of a single skeletal crystal, although their orientation is remarkably consistent.

In general the c-axes of the rods are nearly parallel to the a-axis of a given host perthite crystal, and slope gently toward the observer as the crystal is viewed from the front along its a-axis. In some perthite crystals, however, the rods are much less regularly disposed. Many are plate-like masses, and are grouped in a rudely radial pattern with respect to the a-axes of some host crystals, and the c-axes of others. Many rods appear to be perpendicular or nearly perpendicular to the walls of the enclosing pegmatite dikes, although exceptions are not uncommon. This orientation seems to be in part a reflection of preferred growth of the host perthite crystals along their a-axes.

The coarsest varieties of graphic granite appear to be the least regular in structure. They ordinarily contain rods of bulbous shape, which are distributed in an almost random position in many crystals. In other crystals the rods have a crude radial pattern. Some of the rods are not simple, but instead appear to be skeletal crystals of quartz, with abundant interstitial feldspar. Most are not so elongate as those in the more uniform graphic granite.

Ordinarily the graphic granite contains 15 to 25 percent quartz, although some of it is richer, and consists of unusually large, tapering quartz rods packed very close together. In contrast, much of the coarse perthite in the interior parts of the dikes contains only a few scattered rods. Commonly the rods in such feldspar die out abruptly, either along crystal boundaries or along planes parallel to crystal boundaries but within individual crystals. Elsewhere they decrease in number and die out gradually, so that the graphic granite merges into coarse, blocky perthite without quartz rods.

Although much of the graphic granite is remarkably free from other minerals, particularly in the upper parts of many pegmatites, it is commonly associated with finer-grained aggregates of quartz, muscovite, and albite. These are interstitial to the crystals[42] or crystal groups of graphic granite. Many of these aggregates also contain abundant prisms of schorl, and others are rich in garnet. Muscovite, in foils and plates as much as 5 inches in maximum dimension, commonly forms radiating sprays within

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[42] Although graphic granite is a rock, rather than a mineral, the term "crystal" is used in this report as a convenient means of referring to the host perthite individual.

graphic granite, where it is characteristically associated with fine-grained, sugary albite. In this form it generally has been termed "plumose muscovite." Such fine- to medium-grained mineral aggregates as these ordinarily constitute 5 percent or less of the containing graphic-granite pegmatite, although in some places, particularly in and near those parts of pegmatite dikes of greatest commercial interest, they are more abundant.

The graphic granite of many pegmatites is transected by individual fractures and groups of parallel fractures that in general are conformable with the pegmatite walls. Along many of these fractures are aggregates of quartz, muscovite, albite, and other minerals, chiefly tourmaline and garnet. Some of the fractures contain aggregates of sugary albite, and little else. Fine-grained albite also is widespread along shorter, more irregular fractures, and also occurs as impregnations of irregular shape. Many of these impregnations are extensive, appearing as blanket-like masses as much as 8 feet in diameter.

Other Very Coarse-Grained Pegmatite

Extremely coarse-grained varieties of pegmatite that contain little or no graphic granite occur in many of the dikes, including most of those that have yielded commercial minerals. These varieties are known throughout the district as "giant pegmatite." They consist mainly of quartz or perthite, or both, and in a few pegmatites also contain spodumene. They characteristically form very conspicuous units in the inner parts of the pegmatite dikes. Such units are largest in the thickest dikes, or in bulges in thinner dikes. Where they are chiefly massive quartz, these units form conspicuous white patches on the hillsides, and in many places form small ridges and knobs. Units that are rich in perthite form more subdued, irregular slopes with abundant feldspathic rubble. Many of the exposures are similar in general appearance to exposures of graphic granite. The spodumene-bearing units, in contrast, rarely crop out, even on the steepest slopes.

Most abundant in the thickest dikes are aggregates of very coarse, blocky perthite, occurring as crystals 2 or 3 inches to as much as 8 feet in diameter. The average diameter is about 2 feet. Most of these crystals are equant, but some are elongate in directions parallel to their a-axes. Most of them are subhedral, and are best recognized in outcrops and mine workings by their straight and uniform cleavage faces. The most characteristic colors are white, flesh, and an unusually dark gray. The gray is characteristic of many of the coarsest masses, particularly in pegmatites with abundant lithium minerals, and is in marked contrast to the lighter colors typical of the graphic granite.

Some of the blocky perthite is fairly pure, occurring as very coarse aggregates of dark-gray color. The included plates of plagioclase stand out prominently in such material. Other groups of perthite crystals are associated with much finer-grained aggregates of quartz, sugary albite, muscovite, and tourmaline. Much of the perthite has been fractured, and subsequently mineralized along these fractures, in the same general manner as the graphic granite described above.

Another common type of very coarse-grained, or giant pegmatite consists of individual perthite crystals, or aggregates of several crystals, scattered through a matrix of anhedral quartz. They are typically euhedral, and range in diameter from 1 inch to as much as 10 feet. Most masses are 12 to 18 inches in diameter. The color of these crystals ranges from white through flesh and tan to dark gray. With decreasing quartz content, this rock type grades into the coarse, blocky perthite just described. Toward the centers of some pegmatite dikes, the proportion of perthite decreases, and the rock grades into massive quartz.

Some masses of quartz with individual perthite crystals are fairly pure, but most of them contain small grains of other minerals. Some of the small grains are along continuous and regular fractures, and some are near or along contacts between quartz and perthite. A few pegmatites have anhedral to euhedral crystals of beryl in this quartz-perthite unit. The most characteristic habit of the beryl is prismatic, and some crystals are as much as 2 feet long. This beryl is white, light gray, and pale yellowish green to dark bluish green.

Perhaps the most spectacular type of coarse-grained pegmatite is the so-called massive quartz, which appears as homogeneous masses of gray to milky-white color. Actually, these masses are aggregates of subhedral to anhedral quartz crystals that are 3 inches to 6 feet in diameter. The quartz is characterized by unusually well developed rhombohedral cleavage and very coarse lamellar twinning. In addition it exhibits many growth lines, lines of bubbles and inclusions parallel to crystal boundaries, and layers, $\frac{1}{16}$ to $\frac{3}{16}$ inch thick, of alternately milky and clear material. Some of the quartz contains scattered crystals of feldspar, and grades into the units previously described. Other masses grade into quartz-spodumene aggregates, and still others contain scattered crystals of beryl.

A very striking rock type in many but not in the majority of the pegmatites, consists of lathlike crystals of spodumene in a mosaic of anhedral quartz crystals slightly less than a foot in average diameter. The spodumene ranges from equant crystals about half an inch in maximum dimension to blades and laths as much as 7½ feet long and 2 by 14 inches in section. The average dimensions of the laths, however, are about 18 inches and ½ inch by 3 inches, respectively. Some of the spodumene is relatively fresh, although it appears dull and opaque. Very light gray to yellowish gray are the most common colors. Most of the crystals are considerably altered, and occur in the light to dark-gray quartz as soft, chalky stripes and streaks. Few of them appear to be oriented in any systematic way, and the arrangement in most large exposures suggests groups of jackstraws. Typical exposures are present in the Stewart, Pala Chief, and Katerina mines.

The quartz-spodumene pegmatite in some dikes contains coarse, irregular masses of amblygonite. A few individual crystals are as large as 3 feet, and one aggregate of coarse crystals 18 feet in maximum dimension was encountered in the Stewart mine. Crystals and crystal groups of lithiophilite, some as much as 15 inches in diameter, are associated with the quartz-spodumene rock in a few pegmatites, and occur also in the nearby perthite-bearing parts of the dikes. These coarse crystals are especially common in the Stewart and Katerina mines. Beryl, generally in white to very pale pink, equant crys-

FIG. 4. Aerial view of Little Chief and Chief Mountains, showing westerly dip of the pegmatite dikes. A belt of bouldery granodiorite crosses the area in the middle distance. View is toward the north. SC, Salmons City (abandoned); PC, Pala Chief mine; WC, West Chief pegmatite (broad dip slope); MF, McGee Flats. *Pacific Air Industries photo.*

tals, is scattered through the quartz-rich parts of some quartz-spodumene units, but it is not at all common.

Pocket Pegmatite

The lepidolite and gem-bearing part of a given pegmatite dike in the Pala district is referred to locally as the ''pocket zone,'' ''pay streak,'' ''clay layer,'' ''gem seam,'' or ''gem strip.'' This type of pegmatite ordinarily occurs in the central parts of the dikes, although in some it is within a foot of the hanging wall. It is characterized by fine-grained to very coarse-grained minerals, many of which contain lithium, beryllium, bismuth, boron, caesium and rubidium, columbium and tantalum, flourine, manganese, phosphorus, or combinations of these elements. The most common minerals are quartz, albite, orthoclase and subordinate microcline, muscovite, lepidolite, and tourmaline. Spodumene forms as much as 25 percent of some gem units, but most of the spodumene-bearing rock contains no gem material.

In the strictest sense, the term ''pocket pegmatite'' is a misnomer, as actual cavities are not particularly abundant in most of the pegmatites. In many of the so-called pockets, the minerals are markedly euhedral, but most of the minerals are in contact with one another, and where open space does exist, its relative volume is very small. Other pockets are partly or completely filled with so-called pocket clay, which is characteristic of most of the gem-bearing units in the pegmatites.

Well-formed crystals of quartz are abundant in the pocket pegmatite. Most of them are associated with coarse cleavelandite and aggregates of large foils and plates of muscovite. Well-formed crystals of perthitic orthoclase are abundant in some pegmatites. Few of these crystals exceed 8 inches in maximum dimension, and most are less than 5 inches. Some of the quartz crystals, in contrast, are as much as 3 feet long, and several weighing 100 pounds or more have been recovered during mining operations. Sugary albite also is abundant, and is generally associated with irregular small masses of quartz and aggregates of muscovite, schorl, lepidolite, or combinations of these minerals. Schorl, some of it in prisms as much as 4 feet long, is particularly abundant around the margins of units of pocket pegmatite. In contrast, the green, blue, white, and pink varieties of tourmaline form the central parts of such units.

Marked concentrations of coarse muscovite and schorl, in places associated with garnet, are generally most characteristic of the outer parts of gem-bearing masses. These masses generally contain both very coarse-grained and very fine-grained minerals in close association. The fine-grained minerals, chiefly albite, lepidolite, and muscovite, form compact aggregates, to which coarser crystals of other minerals are commonly attached. Elsewhere these aggregates appear to cover earlier formed, coarser crystals.

Many gem crystals of tourmaline, beryl, and spodumene are attached to quartz or to other typical pocket minerals, and such material is ordinarily referred to as ''frozen.'' The gem material of highest quality, however, is not attached, but is commonly arranged without known systematic distribution within the masses of clay that fill the cavities.

Fine-grained Granitoid Rocks

Unlayered and Poorly Layered Varieties. Fine-grained rocks with typical granitoid texture are well represented in most of the pegmatite dikes, although in general they are not as well exposed as the graphic granite and other coarser varieties of pegmatite. They are most common in the footwall parts of the dikes, and have formed entire dikes in some areas, particularly on Hiriart Mountain and on the north slope of Pala Mountain.

Nearly all these rocks, known in the district as granite, sugar granite, mica aplite, or albitite, are composed mainly of quartz and albite, with or without microcline, muscovite, schorl, garnet, biotite, or other minerals. A sugary texture is characteristic, and the average diameter of individual mineral grains is about 2 millimeters. The garnet crystals ordinarily are smaller, but some of the mica foils and strips are much larger, in places reaching maximum dimensions of half an inch to an inch. Despite these local variations, the rocks are fairly even-grained. Their average color is light gray, and nearly white feldspars contrast sharply with the gray of the quartz.

The uniform, unlayered appearance of these rocks is broken in some places by a very crude but broadly regular planar structure. This structure is commonly formed by ill-defined layers, $\frac{1}{32}$ inch to several inches thick, that are relatively rich in scattered crystals of garnet. Garnet is by no means restricted to such layers, however, but is disseminated through most of the rock. Some layers are relatively rich in mica, and a few in fine-grained schorl. Other layers are relatively rich in quartz, and the layering in still other types of rock is caused by alternations of coarser-grained and finer-grained material of nearly uniform composition.

Ordinarily the groups of garnet-, mica-, and schorl-rich layers interrupt rather homogeneous, unlayered rock. Individual layers are at least $\frac{1}{2}$ inch apart, and are much thinner than the material that separates them. They are uniformly flat, or nearly so, for great distances, but in some places are characterized by broad rolls. Locally they appear to have been folded on a smaller scale, and in a few places are even plicated. The planar structure in some of these fine-grained rocks is emphasized by stringers of younger pegmatite that may have been emplaced along fractures. The fractures follow closely the layering of the rocks, and it is only on a small scale that the later injected material cuts across this structure.

Where the pegmatite dikes are simple in internal structure, the fine-grained granitoid rocks generally pass abruptly upward or downward into graphic granite. As traced along the strike of the dikes, the contact relations at the ends of the fine-grained units are similarly abrupt in some places, but in others the fine-grained rock fades into graphic granite over distances of 2 feet to as much as 20 feet. Where the fine-grained rock is layered, the layers fade out with diminution of their characteristic mineral constituents, rather than taper out sharply.

Much of the fine-grained, albite-rich rock contains ragged masses of graphic granite ranging in maximum diameter from $\frac{1}{4}$ inch to nearly 3 feet. The average size of these masses, some of which appear to be remnants of once more extensive material, is slightly less than an inch. Graphic granite occurs also as tabular masses, some of them discordant but most of them parallel to whatever layering is present in the fine-grained host rock. These younger masses range from stringers less than ¼ inch thick to sills and dikes as much as 8½ feet thick. Many of the thicker dikes of graphic granite are pegmatities in their own right, and show internal structure similar to that of dikes enclosed by gabbroic rocks.

In many places the fine-grained rocks are cut by stringers of aplitic material of similar texture and mineralogy. These stringers are somewhat less regular than the graphic-granite units described above, and most of them fade out along their strike and down their dip. They are similar in many respects to the ''auto-injection'' material so widespread in the earlier gabbroic rocks of the district.

Layered Varieties: Line Rock. One of the most widespread and distinctive lithologic units in the Pala pegmatites is line rock, also well-known as albite aplite, garnet aplite, albitite, zebra rock, stripe rock, garbandite, and bottom rock. Several of these names are derived from its strikingly layered structure, which forms closely spaced, nearly parallel lines on most exposed surfaces.

The line rock is not so resistant to erosion as the graphic granite, but nevertheless in some dikes forms many outcrops. The best exposures of the more resistant, garnet-rich types of this rock are the surfaces of the very large boulders that veneer several landslide masses on the slopes of Hiriart Mountain, and the boulders immediately northeast of Ashley Ranch (pl. 1). This garnet-rich type of line rock seems to be in a greater proportion of the pegmatites on Hiriart Mountain than elsewhere in the district.

The line rock is much like the other varieties of fine-grained granitoid rocks noted above, and indeed grades into them in many places. In general, however, it is finer grained and more distinctly layered. The planar structure is formed by alternations of garnet-rich and garnet-poor layers that generally are 0.5 millimeter to 1 centimeter thick. The average thickness is between 2 and 3 millimeters. These layers occur in a uniformly fine-grained mosaic of quartz, albite, and some muscovite and microcline. A few varieties of line rock are characterized by schorl-rich layers. Beryl, apatite, and monazite are rare accessory constituents of such rock. The garnet-rich and schorl-rich layers are ordinarily separated by several times their thicknesses of quartz-albite rock.

The layers are very uniform in width and spacing for considerable distances along their strike, and in general they are parallel to the walls of the enclosing pegmatite dikes. They are strikingly similar in all respects to the banded garnet phase of some pegmatites in the Owl Creek Mountains of Wyoming, as described by McLaughlin.[43] Some of the layers die out abruptly as traced along their strike, but others fade gradually into a more homogeneous aplitic rock, or into graphic granite. In general the layered rock is not coextensive with the dikes that enclose it, although it is commonly continuous for many tens of feet, both along the strike and down the dip of most dikes.

The strikingly planar structure of most line rock is marked by gentle undulations, which give a nodular or orbicular appearance to the surfaces of masses broken nearly parallel to the general attitude of the layering. In other places, the layers form gently curving loops, which taper or become broader as traced in a direction normal to the walls of the pegmatite. There is some evidence of plastic movement in part of the line rock. Flexures that suggest a uniform direction of dragging are widespread, though not particularly abundant. Piercing folds occur locally, and in most of them line rock in which the layering has been thrown into whorls transects the structure of adjacent undisturbed layers.

Some line rock appears to grade upward into massive quartz, with a gradual diminution of garnet-rich layers and a gradual increase in the distance of their spacing. This transitional rock is very striking in appearance, because of manganese oxide stains derived from alteration of the garnet.

Much of the line rock contains masses of graphic granite with very ragged edges. These masses, markedly similar to those in the more homogeneous fine-grained rocks described above, have been interpreted as residua of much more extensive pre-existing graphic granite by Schaller.[44] On the other hand, much graphic granite occurs in the line rock as distinctly later sills, dikes, and augen. The individual masses ordinarily range in diameter from about an inch to at least 6 inches, and the aggregates that were injected are similar to those in the less well layered, fine-grained rocks described above. Most of them are clearly sill-like, and transect the planar structure of the host rock in very few places. It seems clear, on the basis of numerous exposures throughout the district, that the typical garnet-rich line rock contains at least two generations of graphic granite.

Other Types

Additional rock types are common in the pegmatite dikes of the Pala district, but most of them are transitional between types already described. Others consist of abundant fracture-controlled minerals in graphic granite, in other very coarse-grained pegmatite, or in one of the finer-grained rocks. They vary greatly in texture and mineralogy, and do not lend themselves readily to classification and systematic description.

A few pegmatite lenses and dikes of a wholly different type are within the limits of the district. They range in composition from gabbro to granodiorite, and appear to be more closely related to the exposed batholithic rocks than do the younger and more truly granitic pegmatites described above. Many of them are lenses and irregular stringers of gabbroic pegmatite. Some are very coarse, and contain crystals of calcic plagioclase and hornblende as much as 4 inches in maximum dimension. Few of these basic pegmatites are continuous, and most of them are less than a foot thick and 4 feet long.

Other pegmatites, much more closely related to the principal varieties described in this report, are of tonalitic to granodioritic composition. They contain coarse, white plagioclase—chiefly median to calcic oligoclase—with quartz, biotite, muscovite, garnet, and some black tourmaline but no lithium minerals. Most of these pegmatites are in the northwestern and northeastern parts of the district. Several prospect pits have been sunk in this type of rock east of McGee road and 2000 feet north of the northwest corner of Hiriart Mountain (pl. 1), and

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[43] McLaughlin, T. G., Pegmatite dikes of the Bridger Mountains, Wyoming: Am. Mineralogist, vol. 25, pp. 62-63, 1940.

[44] Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, pp. 271-275, 1925.

Fig. 5. Aerial view of Hiriart Mountain, Katerina mine and Ashley ranch in left foreground, Fargo mine near center foreground, and Vanderburg mine near summit of mountain. Dips of pegmatite dikes are moderate. View is toward the north-northwest. *Pacific Air Industries photo.*

similar openings have been dug farther to the northwest, in an area underlain chiefly by granodiorite.

The pegmatite dikes of intermediate composition are much like those that are truly granitic, as far as general structure is concerned, but are not so continuous along their strike. This lack of continuity is even more characteristic of the gabbroic pegmatites.

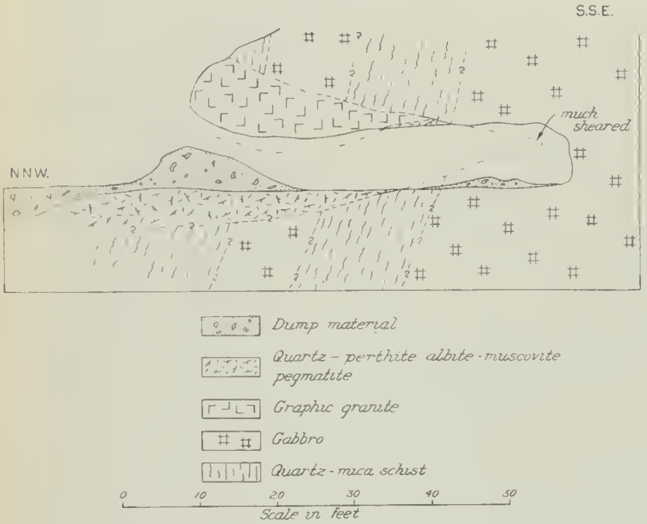

FIG. 6. Section through west tunnel, North Star mine, showing tapered edge of pegmatite dike in gabbro and quartz-mica schist.

Internal Structure

General Features

Many of the Pala pegmatites consist of two or more units of contrasting lithology, as already shown. The distribution of these units within each dike is essentially systematic, and is related—at least in part—to the overall structure of the dike. The disposition of minerals and the pattern of textural variations also follow certain rules within each unit, although there are many irregularities of detail. Most prospectors and mine operators in the district have recognized this orderliness, and the distribution of mine workings bears testimony to their thorough exploration of contacts between line rock and overlying graphic granite in a search for pocket material.

Rock units of contrasting composition and texture have long been recognized in many pegmatites. As early as 1871, for example, T. S. Hunt[45] remarked upon the distinct layering of many "granitic veinstones" in Maine. References to bands, layers, lenses, ribs, segregations, shoots, streaks, and zones of massive quartz and of other minerals or mineral aggregates are common in many early reports. Some investigators were impressed by irregularities of mineral distribution in pegmatites, it is true, but others recognized these as essentially irregularities of detail. During the period 1900-35 it was repeatedly noted that cavities, concentrations of both common and unusual minerals, and concentrations of economically desirable minerals tend to occupy characteristic positions. The attention of most investigators, however, was focused more upon the mineralogy of such contrasting units than upon their structural and petrologic relations.

During more recent years, increasing emphasis has been placed upon interpretation of the internal structure of pegmatites, both as a means of determining their genesis and as an aid in planning exploration, development, and mining.[46] Most workable concentrations of pegmatite minerals are in rock units that differ markedly in one or more respects from adjacent barren units. This has been repeatedly demonstrated by detailed studies in many areas. On the other hand, few homogeneous, or internally structureless pegmatite bodies contain concentrations of commercially desirable minerals sufficiently rich to yield satisfactory returns in mining under present economic conditions.

Three fundamental types of pegmatite units have been recently defined and described[47] as follows:

1. *Fracture fillings* are units, generally tabular, that fill fractures in consolidated pegmatite.
2. *Replacement bodies* are units formed primarily by replacement of consolidated pegmatite. Although there are all gradations between simple fracture fillings and fracture-controlled replacement bodies, the structural control for many replacement bodies is not clear.
3. *Zones* are successive units that ordinarily reflect the shape or structure of the enclosing pegmatite body. In lenslike or podlike pegmatites they have a concentric pattern, and in the more tabular bodies they appear as simple layers. Many zones are not completely developed, and form straight or curving lenses, troughlike or hoodlike bodies, or chains of lenses.

Contacts between adjacent pegmatite units vary considerably in distinctness. Those between units of markedly different composition or texture are commonly of knife-edge sharpness, and often may be mapped on a scale as large as 20 feet or even 10 feet to the inch, whereas some of those between mineralogically similar units are difficult to assign within narrow limits, especially where such units are intergradational or very coarse grained.

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[45] Hunt, T. S., Notes on granitic rocks: Am. Jour. Sci., 3rd ser., vol. 1, pp. 82-89, 182-191, 1871.

[46] See, for example:
Smith, W. C., and Page, L. R., Tin-bearing pegmatites of the Tinton district, Lawrence County, South Dakota: U. S. Geol. Survey Bull. 922-T, 35 pp., 1941.
Olson, J. C., Mica-bearing pegmatites of New Hampshire: U. S. Geol. Survey Bull. 931-P, pp. 373-376, 1942.
Bannerman, H. M., Structural and economic features of some New Hampshire pegmatites: New Hampshire State Planning and Dev. Comm., Min. Res. Survey, Part VII, 22 pp., 1943.
Page, L. R., Hanley, J. B., and Heinrich, E. Wm., Structural and mineralogical features of beryl pegmatites (abstract): Econ. Geology, vol. 38, pp. 86-87, 1943.
Cameron, E. N., Larrabee, D. M., McNair, A. H., and Stewart, G. W., Characteristics of some New England mica-bearing pegmatites (abstract): Econ. Geology, vol. 39, p. 89, 1944.
Jahns, R. H., and Wright, L. A., The Harding beryllium-tantalum-lithium pegmatites, Taos County, New Mexico (abstract): Econ. Geology, vol. 39, pp. 96-97, 1944.
Olson, J. C., Parker, J. M. III, and Page, J. J., Mica distribution in western North Carolina pegmatites (abstract): Econ. Geology, vol. 39, p. 101, 1944.
de Almeida, S. C., Johnston, W. D., Jr., Leonardoes, O. H., and Scorza, E. P., The beryl-tantalite-cassiterite pegmatites of Paraiba and Rio Grande do Norte, northeastern Brazil: Econ. Geology, vol. 39, pp. 206-223, 1944.
Olson, J. C., Economic geology of the Spruce Pine pegmatite district, North Carolina: North Carolina Dept. Conservation and Development, Div. Min. Res., Bull. 43, 1944.
Johnston, W. D., Jr., Beryl-tantalite pegmatites of northeastern Brazil: Geol. Soc. America Bull., vol. 56, pp. 1015-1070, 1945.
Cameron, E. N., Larrabee, D. M., McNair, A. H., Page, J. J., Shainin, V. E., and Stewart, G. W., Structural and economic characteristics of New England mica deposits: Econ. Geology, vol. 40, pp. 369-393, 1945.
Fisher, D. J., Preliminary report on the mineralogy of some pegmatites near Custer: South Dakota State Geol. Survey Rept. of Investigations No. 50, 89 pp., 1945.
Jahns, R. H., Mica deposits of the Petaca district, Rio Arriba County, New Mexico: New Mexico School of Mines, State Bur. Mines and Min. Res., Bull. 25, 1946.
Cameron, E. N., and Shainin, V. E., The beryl resources of Connecticut: Econ. Geology, vol. 42, pp. 353-367, 1947.
Pecora, W. T., Klepper, M. R., and Larrabee, D. M., Mica-bearing pegmatites in Minas Gerais, Brazil (abstract): Washington Acad. Sci. Jour., vol. 37, pp. 370-371, 1947.
Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., The internal structure of granitic pegmatites: Econ. Geology, Mon. 2, 1949.

[47] Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., op. cit., pp. 14-96, 1949.

So varied and uneven are the textures of typical pegmatites that no single term, such as "pegmatitic," suffices for most descriptions. The following size classification of pegmatitic textures, adopted by the U. S. Geological Survey, is used throughout this report:

Term	*General grain size* (in terms of maximum diameter of each grain)
Very fine (includes sugary, aplitic)	Less than ⅛ inch
Fine	⅛ inch to 1 inch
Medium	1 inch to 4 inches
Coarse	4 inches to 12 inches
Very coarse, or giant	Greater than 12 inches

Zones

A grouping of pegmatite zones into four main categories has been proposed by Cameron, Jahns, McNair, and Page [48] as follows:

1. Border zones, or outermost zones.
2. Wall zones.
3. Intermediate zones.
4. Cores, or innermost zones.

According to this classification, pegmatites that are not homogeneous ordinarily range from simple masses with only a border zone surrounding a core to masses with a border zone, wall zone, core, and several intermediate zones. There is no theoretical limit to the possible number of intermediate zones, but few pegmatites in the Pala district contain more than three such units.

The border zones of most Pala pegmatites are thin, inconspicuous selvages. They consist generally of fine-grained graphic granite in which most of the quartz rods are less than 1 millimeter in diameter. The host perthite crystals rarely are greater than 1 inch in maximum dimension, and most of them are less than ½ inch. A few pegmatites are marked by selvages of line rock or other fine-grained material.

The border zones pass into typical coarse-grained graphic granite of the adjacent wall zones with an abrupt increase in grain size. They are in even sharper contact with the country rock, and in some pegmatites shearing has juxtaposed thin slices of gabbro and border-zone material.

In general the outermost zones are an inch or less in thickness, and most are markedly discontinuous. Indeed, relatively fine-grained selvages are absent from many dikes, in which coarse-grained graphic granite lies against the gabbroic country rock. In most pegmatites, the border zones are more widespread along the hanging wall than along the footwall contacts.

In addition to graphic granite, most of the border zones also contain small quantities of fine-grained albite, muscovite, widespread garnet, and some schorl as tiny scattered specks. In general these minerals are rather evenly disseminated, but in a few pegmatites they are arranged in layers parallel to the nearby wallrock contacts. A very regularly layered border zone is well exposed in the workings of the Pala View mine, on the south side of Queen Mountain. Here a selvage of fine-grained graphic granite, ½ to 2½ inches thick, contains small, scattered flakes of pale-green muscovite, and is marked by thin, subparallel layers rich in quartz and garnet. The garnet occurs as deep-red crystals 2 millimeters in maximum diameter. In places where individual layers are at least ¼ inch thick, this mineral forms subgraphic intergrowths in quartz. Most of the garnet-rich layers are near the inner part of the border zone along both the hanging-wall and footwall contacts of the dike.

Wall zones, which represent by far the most abundant pegmatite material in the district, are composed of graphic granite, with or without other minerals. In most pegmatites, substantial quantities of interstitial quartz are present, commonly with subordinate albite, muscovite, and schorl. The typical graphic granite is most abundant and continuous in the hanging-wall parts of the dikes. There is some evidence, first cited by Schaller,[49] that it was once present in the footwall parts, possibly in great abundance, and that it was subsequently replaced by line rock and other types of fine-grained, albite-rich pegmatite. On the other hand, there are many dikes in which such evidence is rare, or does not seem to be present at all, so that the concept of a graphic-granite wall zone, symmetrically developed with respect to a central plane in each dike, cannot be applied with assurance to all of the pegmatites that contain line rock.

Some pegmatites consist almost wholly of graphic granite, and appear to comprise only two zones. In them the typical coarse-grained graphic granite should be termed a core, rather than a wall zone, although it seems probable that quartz-rich core segments are present somewhere in nearly all the dikes that appear to consist wholly of graphic granite.

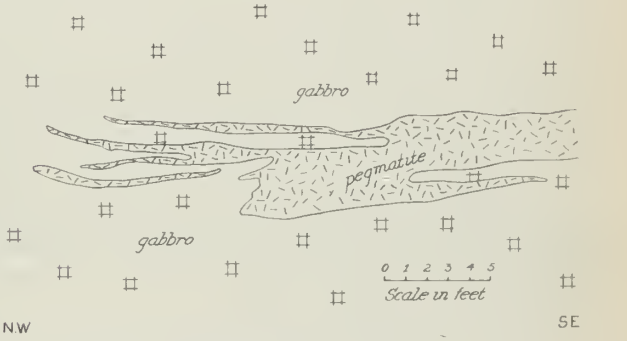

FIG. 7. Sketch of pegmatite-gabbro relations on northeast wall of main tunnel, Pala View mine.

Most of the wall zones are continuous. They constitute almost the full thickness of many dikes, in which they are interrupted only here and there by small segments of cores or intermediate zones (fig. 19). Large parts of other dikes, however, contain well-developed cores, which typically appear as discoidal masses of very coarse-grained pegmatite. These are single masses or rows, and ordinarily occupy central positions within the dikes (fig. 20). Most are markedly elongate, as if in reflection of the containing dikes themselves, and some are as much as 50 feet long. Excellent examples of thin, but continuous cores are exposed in the White Cloud, Tourmaline King, and El Molino dikes, and in the northern part of the Stewart dike. The thicknesses of such units rarely exceed 3 feet in the dikes of regular shape, but in some of those with prominent bulges or protuberances, the innermost zones are more nearly equidimensional. Such cores and core segments are commonly 5 to 15 feet thick, but strike lengths rarely exceed 35 or 40 feet.

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[48] Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., op. cit., pp. 20-21, 1949.

[49] Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, pp. 273-276, 1925.

The thinnest cores and segments of cores consist generally of massive quartz in very coarse-grained aggregates of anhedral crystals, or of such quartz with scattered large euhedral crystals of perthite. In some of these perthite-bearing units, the quartz is the subordinate constituent. Indeed, the cores of a few pegmatites consist almost wholly of very coarse-grained blocky perthite in subhedral to anhedral aggregates. In a few others the cores are massive quartz with scattered lath-shaped crystals of spodumene.

The relations of these simple innermost units are shown diagrammatically in figures 19 and 20A. The subhedral graphic granite, with its local interstitial aggregates of quartz, perthite, and albite of much smaller grain size, typically grades into the central units of coarse, euhedral perthite crystals in massive quartz. Quartz-perthite cores of this type are similar to miarolitic cavities, in that the feldspar crystals seem to have grown into a liquid- or gas-filled cavity, the cavity having been subsequently filled with quartz crystals.

Much less common than these tabular cores are the thick, pod-like cores at or near the centers of distinct bulges in several of the pegmatite dikes. Some of these thick cores consist of large euhedral to subhedral perthite crystals with interstitial massive quartz, and grade into the adjacent graphic granite of the wall zone as described above. Others are composed of nearly pure massive quartz, of massive quartz with giant spodumene crystals, or, rarely, of massive quartz, spodumene, and large anhedral crystals or crystal aggregates of amblygonite. Because of the great mineralogic difference involved, such units are very sharply separated from the adjoining wall zones. Still other cores are separated from the wall zones by one or more intermediate zones, which appear as partial or complete envelopes around the cores. Some of the intermediate zones are so incompletely developed that they appear only as curving lenses or rows of lenses. In a few pegmatites, distinguished by long, subdued bulges, the cores and intermediate zones have the form of discontinuous layers, rather than thick pods.

The general sequence of essential-mineral assemblages from zone to zone within a single pegmatite dike is remarkably consistent throughout the district. A consistency in sequence of textures also is present, so that the zonal lithology as a whole follows a well-defined pattern. In terms of fundamental textural and mineralogic characteristics, the arrangement of zones from the walls of the Pala pegmatites inward is as follows:

1. Fine-grained graphic granite.
2. Coarse-grained to very coarse-grained graphic granite.
3. Perthite, chiefly in aggregates of very large subhedral crystals.
4. Very coarse anhedral quartz (massive quartz) with scattered large euhedral crystals of perthite.
5. Very coarse anhedral quartz (massive quartz).
6. Very coarse anhedral quartz (massive quartz) with large subhedral crystals of amblygonite and euhedral crystals of spodumene.
7. Very coarse anhedral quartz (massive quartz) with large euhedral crystals of spodumene.
8. Very coarse anhedral quartz (massive quartz).

All of these units are known to occur together in only three pegmatites in the district, the Stewart, Pala Chief, and Vanderburg-Katerina. Most of the dikes contain only three or four of the units, generally Nos. 1, 2, and 4; 1, 2, and 5; or 1, 2, 4, and 5. Many of those on Chief and Hiriart Mountains contain No. 7 as well. Units Nos. 3 and 6 are in the thickest dikes only, and No. 6 is rare. Regardless of the number of such units present in a given pegmatite, however, their order conforms to the general sequence outlined above.

Albite and muscovite are irregularly distributed in most of the units and are locally abundant. The zones contain many other minerals also, but these minerals are either minor accessory constituents or appear to have been introduced after the host zones were formed. If all these minerals were taken into consideration in an analysis of the zones, they would complicate but not alter the basic sequence.

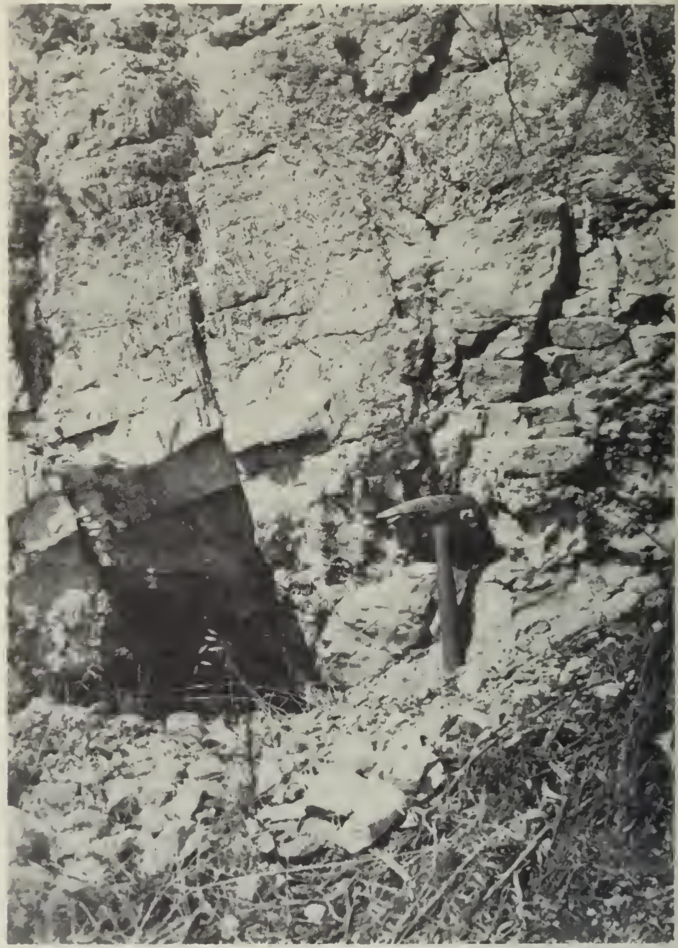

FIG. 8. Large crystals of perthite, with long quartz rods (above level of small opening) overlie a very coarse-grained aggregate of perthite and interstitial quartz, muscovite, and albite. Large crystal of pale yellowish-green beryl is crossed by shadow of hammer handle. Katerina mine.

Fracture Fillings

Most of the fracture fillings consist of quartz, albite, biotite, fine-grained muscovite, or combinations of these minerals, with or without minor accessory constituents. They range in thickness from knife edges to nearly 10 inches, and are most abundant in the outer zones of the pegmatites. Many transect the graphic granite of the wall zones, but merge with inner zones, particularly those very rich in quartz. The exposed parts of others lie wholly within single zones. Still others cut across entire pegmatite bodies, and are plainly younger than all the zones nearby.

Three general types of fracture structures appear to have guided mineral-depositing solutions in the pegmatites. One type, parallel to the pegmatite walls, ordinarily consists of individual subparallel fractures that are spaced ½ inch to at least 2 feet apart. Many of them are so regular in their development that they give the pegmatite a sheeted appearance. A second type, consisting of throughgoing fractures, is somewhat less common. Although these fractures also are regular in their distribution, few of them are very closely spaced. A third type of fracture, irregular but abundant and widespread, includes openings along cleavage directions in feldspar and other minerals, and also less regular openings along boundaries between adjacent mineral grains or through the grains themselves. Some of these fractures contain biotite blades that transect both quartz rods and surrounding host feldspar in the graphic granite of many pegmatites.

The minerals in most fracture fillings have corroded the fracture walls, and there are all gradations between simple open-space fillings and fracture-controlled replacement bodies. In general, the more complex the mineralogy of the fracture-related masses, the more they appear to have been formed by replacement of pre-existing pegmatite.

Some of the fracture fillings are composite, and evidently are the result of repeated fissuring and filling with new material. These are not abundant, but are in numerous pegmatites, notably the White Cloud, Tourmaline Queen, Stewart, Douglass, Ocean View, Little Chief, and several dikes on Hiriart Mountain. The layering is commonly emphasized by alternations of milky and clear quartz, or clear and smoky quartz, or, rarely, of quartz and other minerals.

Other Units

Replacement bodies, many of which are obviously fracture-controlled, are present in nearly all the pegmatites. They are younger than the rock that forms the enclosing zones and their structural pattern is plainly superimposed upon the essentially concentric or layer-like arrangement of the zones. They are composed chiefly of fine- to coarse-grained albite, quartz, and muscovite. Lepidolite and tourmaline also are widespread, but are much less abundant. Numerous accessory species are present in some of the pegmatites, but rarely in more than very small quantities. They include beryl, bismuth minerals, clay minerals, columbite-tantalite, cookeite, manganotantalite, monazite, stibiotantalite, sulfide minerals, topaz, zeolites, and zinnwaldite. Other accessory minerals appear to have been formed earlier, and may well be indigenous to the zonal units of the pegmatites. Apatite, cassiterite, lithiophilite, triphylite, and some beryl, garnet, and schorl are typical examples of these.

The simplest replacement bodies are fracture-related units that have corroded the fracture walls. Perhaps most easily interpreted are those in the hanging-wall zones of graphic granite, in which they are generally parallel to the pegmatite-country rock contacts. They range from 1 millimeter to several inches in thickness, and commonly extend for several tens of feet along the strike. Groups of these units form anastomosing networks where developed along a single set of fractures, and more reticulate networks where their distribution was controlled by two sets of fractures.

On the west face of the south cut of the Stewart mine, excellent examples of fracture-related replacement bodies are near the hanging wall of the pegmatite. Here numerous thinly tabular masses of fine- to medium-grained quartz-albite pegmatite with abundant muscovite and green tourmaline clearly were formed along subparallel fractures in coarse-grained graphic granite. These units cut across individual crystals of perthite, and also across quartz rods and groups of such rods in the graphic granite. Thinner and more widely spaced replacement bodies are exposed in the main cut of the Tourmaline Queen mine. They are composed mainly of quartz and muscovite, with local concentrations of albite, tourmaline, and lepidolite.

Comb structure, with platy to pencil-like crystals oriented normal to the walls, is fairly common in the most tabular fracture fillings. The interiors of these units are marked in many places by sharply terminated crystals of quartz, cleavelandite, muscovite, lepidolite, and tourmaline. Individual crystals are rather small, especially where they are in the outer parts of the host pegmatites. Some of the replacement units contain crude layers, distinguished mainly by variations in quartz, muscovite, or tourmaline content. Some of this layering seems best ascribed to repeated fissuring and introduction of additional material. Other layers evidently were formed by diffusion processes, as they appear to be superimposed upon a coarser textural pattern. Many of these replacement bodies are layered only around a few scattered voids where crystals of tourmaline and lepidolite are more abundant than elsewhere.

Fracture-controlled replacement bodies are not confined to the hanging-wall parts of the dikes, but are also in line rock and other fine-grained granitoid units that commonly form the footwall parts. Most of them are essentially concordant with the planar structure in the line rock, or with the pegmatite-wall rock contacts or contacts between zonal units within the pegmatites. Many of these concordant units are as much as 50 feet long, but most do not exceed 6 feet in maximum dimension. Like those in the hanging-wall parts of the dikes, they commonly branch and join. Elsewhere they are connected by markedly discordant masses of similar material, so that the whole represents ladder veins or larger, reticulate masses. In a few pegmatites, notably the Naylor, replacement units occupy positions in the crests and troughs of warps and tighter folds in line rock. They resemble small phacoliths, with saddlelike or troughlike form.

There are all gradations between fracture-controlled replacement bodies that form series of parallel layers and those that form intricate stockworks. The variations are particularly well illustrated by tabular masses of cleavelandite in very coarse-grained aggregates of quartz. In the White Cloud, Pala Chief, and several other pegmatites, such cleavelandite aggregates were developed along closely spaced parallel fractures in milky to dark-gray quartz, and the two minerals form a strikingly layered rock known throughout the district as zebra rock, banded rock, or stripe rock. Elsewhere, as in the Stewart and Katerina pegmatites, the albite forms reticulate or irregularly ramifying veinlets that transect individual crystals in the quartz aggregate. All stages of replacement can be recognized, and in some places only remnants of quartz, representing the cores of original fracture blocks, attest the former existence of a massive quartz unit. Similar relations are characteristic of much lepidolite and muscovite formed in quartz.

FIG. 9. Large graphic-granite mass surrounded by much finer-grained aggregate of quartz, muscovite, perthite, and albite.

Mineral aggregates similar to those that form replacement units in the outer parts of the pegmatites are more abundant in the central parts of many dikes, but their origin is not so plain. Almost without exception, they appear to be younger than the rock that surrounds them, and in most places they clearly corrode this rock. Whether or not most of them were formed wholly at the expense of this rock is not readily demonstrated, however, for residual masses of earlier pegmatite are rare in their central parts. Nevertheless, these mineral aggregates are here provisionally termed replacement units (possibly in large part of deuteric origin), because of differences in age, texture, and structure between them and the typical zonal units.

These younger units include much of the pocket pegmatite in the district. They range in form from the thinly tabular tourmaline-quartz pockets of such pegmatites as the Fargo and Tourmaline Queen to thickly ellipsoidal lepidolite-rich masses like those in the Stewart pegmatite. Thicknesses range from slightly less than 1 millimeter to about 30 feet, lengths from about 1 inch to as much as 200 feet. Typically these masses are discoid in general shape, but they are so irregular in detail that they appear in most exposures as blobs or splotches. This lack of clear-cut form is further emphasized by the widespread tendency of such units to grade outward into complex systems of fracture-fillings and fracture-guided replacement masses.

Whereas the smallest and most nearly tabular replacement units are widespread in their distribution, the largest and more bulbous ones ordinarily are restricted to the central parts of the host dikes. More specifically, masses of this pocket pegmatite occur in cores and immediately adjacent zones, chiefly along the footwalls or in the footwall parts of the cores and core segments. It does not occur simply along contacts between line rock and overlying graphic granite, as commonly alleged, although it must be admitted that the tops of the main masses of line rock are near the footwalls of the cores and core segments in many of the dikes. Such pegmatite thus is ordinarily most abundant in the central parts of bulges in single dikes or junctions of two or more merging dikes. It is also localized in the nearly flat, terracelike parts of several dikes, as pointed out by Donnelly.[50] To what extent such correlation with gently-dipping parts of the dikes can be generally applied in the district is not yet known.

The structure of the fine-grained granitoid rocks common in the footwall parts of most Pala pegmatites is quite distinct from that of the zones, fracture fillings, and replacement units described above. The masses of fine-grained, albite-rich rock commonly occupy the lower, or footwall, one-fourth to one-half of pegmatite dikes in which the remainder of the rock is graphic granite or graphic granite with small segments of very coarse-grained pegmatite. Some of these masses are composed of line rock and others wholly of aplitic rock without planar structure, but most of them contain both rock types. Indeed, there are all gradations between them, both along and across the strike. As shown in figure 25C, the line rock is commonly separated from the footwall contact of many dikes by 6 inches to nearly 10 feet of aplitic rock that is not layered.

These albite-rich rocks are not confined to the lower parts of the pegmatite dikes, although they are most abundant there. They occur also in the upper parts and even along a few hanging-wall contacts, where they form poorly defined tabular masses (fig. 25D). Where such masses are present in the hanging-wall zones of graphic granite, they impart a crudely layered appearance to weathered surfaces of the pegmatites. Line rock occurs within the cores of a few dikes and appears to be in part superimposed upon the very coarse-grained pegmatite that typically forms these innermost units. Thus it is markedly quartzose where best developed, and commonly grades into much coarser pegmatite containing only a few garnet- or albite-rich layers. In many places it appears to have encroached upon the footwall parts of cores and core segments (fig. 25C).

Where two subparallel pegmatites branch or join, the distribution of line rock generally is like that indicated in figure 8E. The line rock in the lower dike is continuous, whereas that in the upper one fades into the graphic granite or other zonal rock at some distance from

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[50] Donnelly, M. G., The lithia pegmatites of Pala and Mesa Grande, San Diego County, California: California Inst. Technology, unpublished Ph.D. thesis, p. 56, 1935.

the point of junction. This distance ranges from a few inches to many tens of feet, but ordinarily is 10 feet to 30 feet. These relations are characteristic also of the aplitic rocks that lack planar structure.

The structural relations of line rock and associated types in the more bulbous pegmatites are not so clear, owing to the rarity of critical exposures. In general, however, the fine-grained units occupy the lower, or footwall, parts of the dikes, and appear to have encroached upon the inner zones. As exposed in the underground workings of the Stewart, Pala Chief, and Katerina mines, the aplitic rocks are much more continuous than the nearby cores and intermediate zones, both along the strike and down the dip.

Not only are the fine-grained granitoid rocks quite distinct texturally from the other rock types in the pegmatites, but the thin and regular layering in the line rock is an unusual feature. Moreover, these rocks form tabular units that are not symmetrically disposed with respect to the walls of the enclosing dikes, either broadly or in detail. This is in sharp contrast to the relations of the zones, most of which at least tend to be symmetrical.

There seems to be a widespread impression among those who have read reports on the Pala pegmatites that the bulk of the material in these dikes is of replacement origin. This is not correct. In few of the dikes, for example, do the coarse-grained replacement units appear to constitute more than 1 percent of the total pegmatite material present. Even if the various types of aplitic, albite-rich pegmatite in the district were to be interpreted as having been formed at the expense of pre-existing pegmatite, the sum of replacement material still would be less than the amount of graphic granite and other rock types indigenous to the earlier-formed units. In one way or another, this has been pointed out—although admittedly not emphasized—by most previous investigators in the district. In his classic paper on the genesis of the pegmatites, Schaller [51] indicates, for example, that graphic granite is virtually the sole constituent of some dikes and is abundant in most others, and that the graphic-granite pegmatites "have been affected but very little by replacing solutions . . ." This statement is made despite the fact that he considers little material but the microcline in the graphic granite to have been formed by processes other than replacement.

Composite Dikes

Many of the Pala pegmatites are sub-parallel dikes that join with or branch from one another. As shown in plate 1, they are particularly common on Hiriart Mountain. Many do not actually join, but are separated by screens or partitions of wallrock 6 inches or less in thickness. Other juxtaposed dikes are in actual contact, either locally or for considerable distances along their strike, or dip, or in both directions (fig. 34). Their respective identities are preserved over the entire areas of contact, as shown by their individual internal structures, and by the presence here and there of country-rock films between them. Still other dikes appear to mix, or merge with one another, generally at distances of several tens of feet from the points of junction.

The composite nature of many dikes is reflected by repetitions of line rock or other units of aplitic rock within them, and by the slivers and seams of wallrock separating the individual elements of the dikes. Repetition of line rock and associated types is by no means a reliable criterion, however, as these units are in several zones in some pegmatites that plainly are not composite.

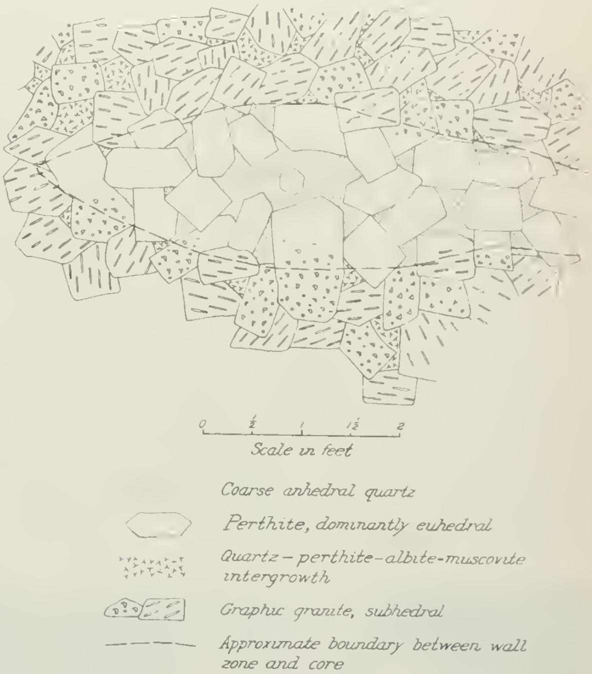

FIG. 10. Diagrammatic sketch showing typical relation between wall zone rich in graphic granite (outside the dashed line) and core segment of quartz and euhedral perthite; simply zoned pegmatite dike.

Much more certain is the evidence of repeated zoning, such as the occurrence of cores or other inner zones at more than one consistent horizon within a given dike. Many of these dikes, as traced along the strike, split into two or more separate dikes, in each of which is preserved the internal structure of the corresponding part of the composite.

Large composite dikes in the district include the Stewart, Pala Chief, San Pedro, Vanderburg, Katerina, and El Molino. In the vicinity of the Gem Star mine, the Stewart dike consists of at least three subparallel branches, or "splits," with intervening septa of gabbro. It is composite also where exposed in the main quarry of the Stewart mine. On the west wall of this quarry a layer of graphic granite 5 to 9 feet thick is overlain by a 5-foot zone of massive quartz with giant euhedral perthite crystals. It is underlain by a very thick zone rich in coarse, blocky perthite, and this unit in turn is underlain by rock similar to that overlying the graphic granite. A contact between two juxtaposed pegmatites is present within the graphic-granite mass, and careful inspection of the quarry face indicates the position of this contact along a thin layer of much finer-grained graphic granite.

Line rock also is repeated at three different stratigraphic positions within the El Molino pegmatite in the vicinity of the main mine workings. Here two thin dikes lie above a much thicker one, and are separated from it in a down-dip direction by a distinct wedge of granodiorite. Along the outcrop, however, all three dikes are in direct contact for almost the full length of the mine area.

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[51] Schaller, W. T., op. cit., pp. 271-277, esp. p. 275, 1925.

Another, very widespread type of composite pegmatite body consists of sills and dikes of graphic granite and other perthite-rich pegmatite in much larger host masses of fine-grained, albite-rich pegmatite. They are particularly abundant on Hiriart Mountain. The masses of younger pegmatite range from thin stringers to sills as much as 8½ feet thick. These younger elements of the composite masses are remarkably continuous along their strike. Some are single sills, others in groups or even swarms of subparallel sills. Most of them are simple aggregates of graphic granite, commonly with bladed biotite and muscovite, albite, and some garnet. Others, especially the larger ones, have symmetrical internal structure, with wall zones of graphic granite and inner zones of other very coarse-grained pegmatite. In several composite dikes, notably the Fargo on Hiriart Mountain, mining has been successfully carried on in such zoned masses, which are surrounded by earlier fine-grained granitoid rock.

In a sense, the composite dikes are merely those in which fracture fillings of later pegmatite are present. Some of these fillings plainly have corroded the fracture walls. The distinction between fracture fillings that are basically minor parts of a single dike, on the one hand, and those that are separate intrusive elements in a composite dike, on the other, is necessarily an arbitrary one, as there are all gradations between the two extremes.

FIG. 11. Euhedral crystals of perthite in massive quartz, El Molino mine. Note the narrow cavities at right-hand margin and lower right corner of large perthite crystal.

Mineralogy

General Features

It is not the purpose of this report to discuss in full detail the minerals of the Pala pegmatites, nor to annotate the voluminous literature on this subject. Descriptions of some of the minerals have been recorded from time to time,[52] and much additional information obtained by Waldemar T. Schaller awaits publication.

The minerals noted and recorded from the Pala pegmatites are listed in table 3. Most abundant and widespread among them are albite, biotite, garnet, lepidolite, microcline and orthoclase (generally perthitic), muscovite, quartz, spodumene, and tourmaline. The most common of the minor constituents are amblygonite, beryl, clay minerals, columbite-tantalite, and lithophilite and associated phosphate species. The relative abundance of the various minerals indicates that the pegmatites are truly granitic in composition, and that many are unusually rich in lithium. Other elements present in noteworthy quantities are beryllium, columbium and tantalum, manganese, and phosphorus, and in lesser quantities bismuth, fluorine, iron, caesium, and rubidium. Antimony, copper, and tin are rarer constituents of the pegmatites.

The principal minerals of the pegmatites, quartz and potash feldspar, are supplemented in most parts of the district by several other species. Muscovite, albite, and garnet are present in all the pegmatites, and generally are widely scattered through each dike. The black variety of tourmaline, schorl, also is widespread. The gem varieties of tourmaline, though less common, are present in many dikes. Most of the pink tourmaline in the district is on Queen Mountain, where it is associated with blue and green varieties. Gem tourmaline is much less common farther east in the district, where most of it is green or yellow green.

Spodumene is abundant in a few dikes, and is a much less common constituent of others. It seems to be rare or absent in most of the dikes west of the Stewart on Queen Mountain, but is exceptionally abundant in the Stewart dike. Large quantities of this mineral are present also in the Pala Chief and Vanderburg-Katerina pegmatites. In general, spodumene makes up a higher proportion of the dikes in the central and eastern parts of the district than in the western part. It is very rare in the pegmatites on Pala Mountain, south of the San Luis Rey River. The same generalizations apply to the known distribution of the clear, gem variety of spodumene, and also to amblygonite and other lithium phosphate species.

Lepidolite is a characteristic associate of both spodumene and tourmaline, but is more widely distributed than either of these minerals. It is common in the pegmatites on Queen Mountain, where most of the gem tourmaline mines have been developed, and is found also in the spodumene-bearing pegmatites of Chief Mountain and Hiriart Mountain. Beryl also is widespread, but seems to be more abundant in the central and eastern parts of

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[52] See for example:

Kunz, G. F., Gems, jewelers' materials, and ornamental stones of California: California State Min. Bur. Bull. 37, pp. 46-101, 1905.

Murdoch, Joseph, Crystallography of hureaulite: Am. Mineralogist, vol. 28, pp. 19-24, 1943.

Schaller, W. T., Spodumene from San Diego County, California: California Univ. Dept. Geol. Sci. Bull., vol. 3, pp. 265-275, 1903.

Schaller, W. T., Notes on some California minerals: Am. Jour. Sci., 4th ser., vol. 17, pp. 191-194, 1904.

Schaller, W. T., Mineralogical notes: U. S. Geol. Survey Bull. 262, pp. 121-122, 139-140, 143-144, 1905.

Schaller, W. T., Bismuth ochers from San Diego County, California: Am. Chem. Soc. Jour., vol. 33, pp. 162-166, 1911.

Schaller, W. T., Notes on purpurite and heterosite: U. S. Geol. Survey Bull. 490, pp. 72-79, 1911.

Schaller, W. T., New manganese phosphates from the gem tourmaline field of southern California: Washington Acad. Sci., Jour., vol. 2, pp. 143-145, 1912.

Sterrett, D. B., Tourmaline from San Diego County, California: Am. Jour. Sci., 4th ser., vol. 17, pp. 459-465, 1904.

Table 3. List of minerals in pegmatites of the Pala district (observed by present writers except where otherwise noted).

Mineral	Pegmatites on Queen Mountain	Pegmatites on Hiriart Mountain	Pegmatites on Chief Mountain and elsewhere
Albite	X	X	X
Amblygonite	xx	x	x
Andalusite	x	---	x
Apatite	x	x	---
Arsenopyrite	*	*	---
Bavenite	---	---	*
Bertrandite	---	*	*
Beryl	xx	xx	xx
Aquamarine			
Cat's eye			
Common			
Golden			
Goshenite			
Morganite			
Beyerite	x[a]	x	---
Biotite	X	X	X
Bismite	x	x	x
Bismuth	x	x	---
Bismuthinite	x	x	x
Bismutite	x	x	x
Bornite	*	*	---
Cassiterite	---	*	---
Chalcedony	x	x	x
Chalcocite	*	*	---
Chrysocolla	x	x	x
Clay minerals	xx	xx	xx
Endellite			
Halloysite			
Kaolinite			
Montmorillonite			
Columbite-tantalite	x	xx	x
Cookeite	x	x	x
Epidote	x	x	x
Garnet	X	X	X
Andradite			
Grossularite (essonite)			
Spessartite			
Helvite	*	*	---
Hematite and goethite	x	x	x
Heterosite	*	*	*
Hureaulite	x	x	x
Lepidolite	X	X	xx
Lithiophilite	xx	x	x
Loellingite	*	*	---
Magnetite	x	x	x
Malachite	*	*	*
Manganese oxides	xx	x	x
Manganite			
Psilomelane			
Manganotantalite	x	x	x
Microcline	X	X	X
Microlite	x	---	---
Molybdenite	---	*	*
Monazite	x	x	x
Muscovite	X	X	X
Oligoclase	x	x	x
Opal	x	x	x
Orthoclase	xx	xx	xx
Palaite	*	*	*
Petalite	*	*	---
Phenakite	---	*	---
Pollucite[b]	x	x	x
Pucherite[c]	x	x	x
Purpurite	x	x	x
Pyrite	x	x	x
Quartz	X	X	X
Salmonsite	x	x	x
Sericite	x	x	x
Sicklerite	x	x	x
Siderite	*	---	*
Spinel	x	x	x
Gahnite			
Hercynite			
Pleonaste			
Spodumene	X	xx	xx
Common			
Hiddenite			
Kunzite			
Triphane			
Stewartite	x	x	---
Stibiotantalite	---	*	---
Strengite	x	x	x
Topaz	---	x	*
Tourmaline	X	X	X
Achroite, Emeralite, Indicolite, Rubellite, Schorl			
Triphylite	x	x	x
Triplite	x	x	---
Vivianite	*	*	---
Zeolite minerals	x	x	x
Heulandite, Laumontite, Stilbite			
Zinnwaldite	*	*	*

* Very rare.
x Not common
xx Common, or abundant in at least one pegmatite.
X Abundant and widespread.
--- Not observed.

[a] Reported by Clifford Frondel in Mineralogy of the oxides and carbonates of bismuth: Am. Mineralogist, vol. 28, pp. 532-533, 1943.

[b] Reported by Adolph Pabst in Minerals of California: California State Div. Mines, Bull. 113, p. 229, 1938.

[c] Reported by W. T. Schaller in Bismuth ochers from San Diego County, California: Am. Chem. Soc. Jour., vol. 33, pp. 162-166, 1911.

* Very rare; x—not common; xx—common, or abundant in at least one pegmatite; X—abundant and widespread; ---—not observed.

the district than elsewhere. Common beryl is locally abundant in the Stewart dike.

The minor accessory constituents are sporadic, but in general are more abundant in the complex, multi-zoned pegmatites than elsewhere. The greatest variety and bulk of accessory mineral material have been obtained from such pegmatites as the Stewart, Pala Chief, and Vanderburg-Katerina. The Tourmaline King, Tourmaline Queen, Anita, Senpe, and El Molino pegmatites also have yielded notable quantities of the relatively rare minerals.

FIG. 12. Coarse perthite and quartz. Perthite crystals are fringed with aggregates of muscovite and albite. Schorl crystals are large.

Principal Minerals

Microcline and Orthoclase. Microcline, the most abundant mineral in the Pala pegmatites, occurs as white, gray, and tan crystals that range from about ¼ inch to 8 feet in maximum dimension. These crystals are anhedral to subhedral in coarse-grained aggregates of graphic granite or in finer-grained quartz-perthite-muscovite-albite pegmatite, and euhedral in most very coarse grained varieties of pegmatite. The lighter-colored crystals are especially common in the outer parts of the pegmatites. In

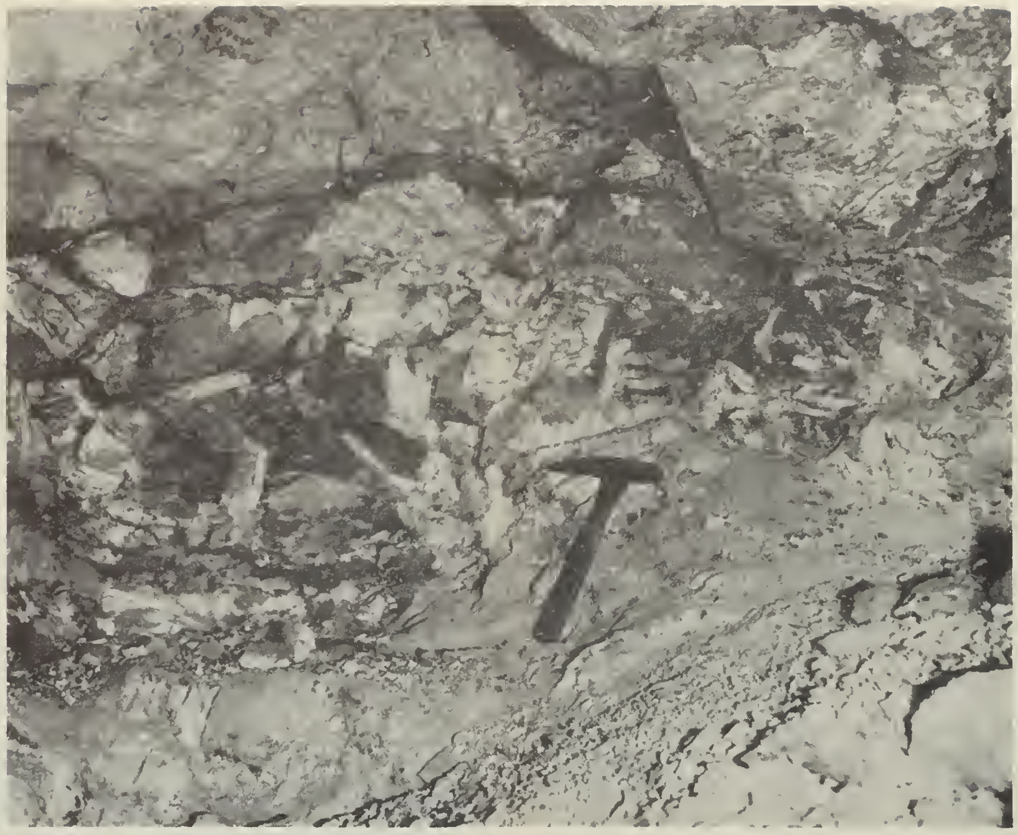

FIG. 13. Coarse-grained quartz-spodumene pegmatite exposed in wall of low room, Pala Chief mine.

general they occupy the full thickness of only those dikes that contain no inner units of very coarse-grained pegmatite or pocket pegmatite. The gray varieties, many of them of very dark shade, are typical of cores and intermediate zones that consist of very coarse-grained pegmatite other than graphic granite. They are most abundant in those dikes that have a very complex internal structure.

Nearly all of the microcline contains perthitic intergrowths of albite and albite-oligoclase as subparallel blebs and plates ordinarily less than 1 millimeter thick and 1 centimeter long. Some very thin plates, however, are much longer than this. In general the largest plagioclase individuals are in the coarsest host crystals of microcline, and hence are most common in the inner zones of the pegmatites. The plagioclase of the perthite also shows a systematic variation in composition, becoming progressively more sodic from the walls of the pegmatite inward.

Orthoclase and microcline are widespread constituents of the pocket zones in the pegmatites, where they generally form large, equant crystals with well-developed faces. They are known among miners and mineral collectors in the district as pocket spar crystals. They are $\frac{1}{2}$ inch to at least 15 inches in diameter, and their faces are characteristically flat and meet in sharp lines. Many of the crystals are transparent, and others are white to light-gray. All are coarsely perthitic. The crystal faces are commonly corroded to depths of $\frac{1}{4}$ inch, and the intergrown plagioclase, evidently much more resistant to corrosion than the host potash feldspar, stands out on such surfaces as narrow, sharp ridges. Many of these corroded surfaces are marked by thin films of iron oxide.

The orthoclase is intimately associated with perthite, and is more abundant than the perthite in the pocket pegmatite of some dikes. In general, however, the orthoclase constitutes only a small fraction of the total potash feldspar within the dikes as a whole. Thin-sections of most orthoclase crystals show irregular patches with the typical gridiron twinning of microcline. In testing the theory that inversion of orthoclase to microcline is commonly caused by strains set up during the grinding of a thin-section, Donnelly[53] prepared several sections by various means, but found no significant variations in the proportion of triclinic feldspar. On the other hand, he did find the typical gridiron twinning of microcline to be more common in thin-sections than in crushed fragments obtained from the same specimen.

Many of the pocket spar crystals of perthitic orthoclase are coated with glassy, transparent, nonperthitic microcline, and the two potash feldspars[54] are in essential crystallographic continuity. Most of these coatings are less than $\frac{1}{4}$ inch thick. Like the host crystals of orthoclase, many are deeply corroded.

Quartz. Quartz is in virtually all of the pegmatite units, and evidently was formed during all general stages of pegmatite development. It is present as spindles, rods, and other elongate masses in graphic granite, and is a major constituent of line rock, of other fine-grained albite-rich types, and of the fine- to coarse-grained aggregates of

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[53] Donnelly, M. G., The lithia pegmatites of Pala and Mesa Grande, San Diego County, California: California Inst. of Technology, unpublished Ph.D. thesis, pp. 68-70, 1935.

[54] Throughout these studies, orthoclase and microcline were distinguished under the microscope on the basis of extinction with respect to the (001) and (010) cleavage traces.

albite, muscovite, tourmaline, and other minerals. It forms large groups of very coarse, anhedral crystals in coarse-grained pegmatite of various types. It fills fractures, forming veinlike masses in potash feldspar and other minerals, and, finally, it occurs in pocket pegmatite as crystals with well-developed faces.

The quartz is milky white to light-gray, but both smoky, and clear, colorless varieties are in the interior parts of many dikes. Its coarsest form is as anhedral crystals 6 inches to at least 6 feet in diameter, and in some pockets as well-formed prismatic crystals that range in length from an inch to as much as 3 feet. Many of them are distinctly smoky. The anhedral crystals are distinguished by rhombohedral cleavage and coarse, lamellar twinning. Individual lamellae are 0.5 millimeter to 10 millimeters thick. Much of this quartz is separated into crystallographic zones by groups of growth lines and roughly planar aggregates of finely divided impurities. A few appear to be phantom crystals without the outer crystal faces.

Albite. Albite is very abundant in the pegmatites, both as fine-grained, sugary, crystalline aggregates (Ab_{90-97}) and as parallel or radiating groups of coarse cleavelandite crystals (Ab_{94-99}). The fine-grained variety of albite is lustrous and white, and is most abundant in line rock and related aplitic units. It is common also in fine- to coarse-grained aggregates of quartz, muscovite, and schorl that are interstitial to graphic granite or to pegmatite composed of coarse euhedral perthite in massive quartz.

Much sugary albite occurs along fractures and cleavage cracks in potash feldspar, and pseudomorphs of albite after such feldspar are not uncommon. Some pseudomorphs of sugary albite appear to have been formed after graphic granite, through selective replacement of potash feldspar by plagioclase. Most of the quartz rods are residua, and show their original orientation and much of their original shape. A great deal of attention has been devoted to this type of evidence by W. T. Schaller, who has used it to demonstrate large-scale albitization of graphic granite.

Fine-grained albite occurs also as perthitic spindles and plates in coarse microcline and orthoclase crystals.

Cleavelandite is generally present in cores and other inner units of the pegmatites, and is locally very abundant. Most of it is white, but pale apple-green and some bluish varieties are not uncommon. The platy crystals are ¼ inch to as much as 3 inches long, ⅛ inch to 2½ inches wide, and 1/32 to ⅛ inch thick. Many of them are curved or warped, and others are flat, with broadly curving ends. The mineral is characteristically twinned, and shows very thin lamellae.

All varieties of the plagioclase generally form aggregates that, where relatively free from other minerals, crumble when struck with a hammer.

The coarse albite is present chiefly along fractures in quartz, perthite, spodumene, and other relatively early minerals; along contacts between such minerals, especially spodumene and quartz; as irregular aggregates with quartz and muscovite; and as cavity linings in pocket pegmatite. Where it is distributed along fractures or mineral contacts, individual crystals tend to lie with their broad surfaces perpendicular to these planar features. Elsewhere they form sheaflike or rosettelike aggregates.

FIG. 14. Matrix specimen from richest gem-bearing part of dike, Pala Chief mine. Short, bladelike crystal of spodumene (upper right) in cleavelandite and quartz. Large crystals and aggregates of lepidolite flakes at left. *Photo by courtesy of Monta J. Moore.*

Beautifully formed groups of coarse cleavelandite blades commonly fringe crystals of quartz, potash feldspar, spodumene, and muscovite in the pocket-rich parts of the pegmatites.

Micas. Muscovite is present in all the pegmatites, and is a common constituent of most of them. It is scattered through the line rock and related granulitic types as white to very pale green flakes and foils that rarely exceed 1 millimeter in diameter. Similar thin crystals occur locally in graphic granite and other coarse-grained, perthite-rich pegmatite. Individual crystal plates range in diameter from 0.2 millimeter to 3 millimeters. Much coarser plates are present in aggregates of quartz, albite, and tourmaline that are interstitial to large crystals or crystal groups of graphic granite, perthite, or coarse, anhedral quartz with perthite crystals.

The inner parts of many pegmatites contain very coarse-grained muscovite, which is characteristically associated with albite and quartz. The crystals, or books, are well formed in pocket pegmatite, and attain diameters of several inches with thicknesses of as much as an inch. Average dimensions, however, are approximately $\frac{1}{2}$ inch and $\frac{1}{8}$ inch, respectively. The mineral characteristically ranges from yellowish green to dull, pale to deep green, and is generally marked by ruling and herringbone structure. Some books are so severely marred by fine, closely spaced crenulations that they appear silvery white and opaque. Many contain inclusions of green to very dark blue-green tourmaline, and some are fringed with lepidolite. The lithia mica ordinarily is crystallographically continuous with muscovite, so that the two minerals form zoned crystals with pink margins and green centers. Some have intermediate zones that are yellow to white.

Muscovite occurs also in the inner pegmatite units as nearly pure aggregates of $\frac{1}{8}$-inch to $\frac{1}{2}$-inch plates. Most of these aggregates are 3 inches to about 6 feet in maximum dimension. Locally they contain quartz, albite, and scattered prisms of green or black tourmaline. Some of these aggregates fill fractures in other minerals, especially in coarse, anhedral quartz.

Tabular to equidimensional masses of extremely fine-grained muscovite occur in a few pegmatites. Some of these masses are distinctly podlike. The mica is very pale green, and is generally so fine-grained that it has a waxy appearance. The aggregates, which are rarely greater than 4 inches in maximum dimension, are most abundant along fractures or at fracture intersections.

Biotite is a common, but quantitatively minor mineral in the outer parts of nearly all the pegmatites. It is typically associated with muscovite, both in graphic granite and in the fine-grained rocks that are so abundant in the footwall parts of the dikes. Individual plates and blades of this mineral generally range from $\frac{1}{4}$ inch to 4 inches in diameter or length. All are very thin, and most of them form mere "skims" in the host rock. Some are slightly altered, and are stained with iron oxides.

The biotite occurs as isolated crystals, as dense aggregates of small foils, and as subparallel to radiating groups or sprays of broader and thinner crystals. In many places individual crystals transect the quartz rods in graphic granite and also boundaries between mineral grains, and clearly were formed along fractures. Elsewhere they are intergrown with other minerals as if they had crystallized with them. Much of the bladed biotite near the hanging-wall contacts of the dikes is oriented normal or nearly normal to these contacts. Possibly much of this biotite was developed as a result of reaction between pegmatite solutions and the gabbroic country rock.

Lepidolite is one of the most characteristic pocket minerals. Where best developed, it forms compact aggregates of thick flakes and plates 2 millimeters or less in diameter. These aggregates are present as lenses and pods less than a foot thick in most pegmatites, but in others, notably the Stewart, they are 10 to 15 feet thick and many tens of feet long. They range in color from pale rose to deep lilac or even purple. The coarsest flakes ordinarily are lightest in color, whereas most of the purplish aggregates are extremely fine-grained, with a waxy appearance.

Although most masses of fine-grained lepidolite are in the innermost parts of the pegmatites, some markedly tabular aggregates of this mica and albite, quartz, and tourmaline fill fractures in the graphic granite and coarse-grained quartz-perthite units of several pegmatites. Excellent exposures are in the hanging-wall parts of the Tourmaline King, Tourmaline Queen, and Stewart dikes.

Fig. 15. Fine-grained granitoid rocks. Boulder with exposed face nearly perpendicular to garnet-rich layering. Note variations in thickness, sharpness, and spacing of layers. South side of Hiriart Mountain.

Coarse-grained lepidolite occurs only in the typical pocket pegmatite, where it is most commonly associated with muscovite, albite, quartz, and lithia tourmaline. Most individual crystals are $\frac{1}{4}$ inch to 2 inches in diameter, with thicknesses of $\frac{1}{8}$ inch to $1\frac{1}{2}$ inches. Many are tightly intergrown in a manner similar to the much smaller individuals in the compact aggregates described above. In contrast, some aggregates of lepidolite and cleavelandite are markedly cellular, with numerous irregular voids $\frac{1}{8}$ inch to $\frac{3}{8}$ inch in diameter. Elsewhere these two minerals occur as well-formed crystals that line clay-filled cavities. Plates of lepidolite commonly are attached to earlier crystals or crystal aggregates of cleavelandite and quartz. The lithia mica forms the outer parts also of composite muscovite-lepidolite crystals, as already noted.

Garnet. Of the several kinds of garnet in the pegmatites, an iron-bearing representative of the manganese-aluminum variety, spessartite, is the most widespread. It forms dodecahedral and trapezohedral crystals that range

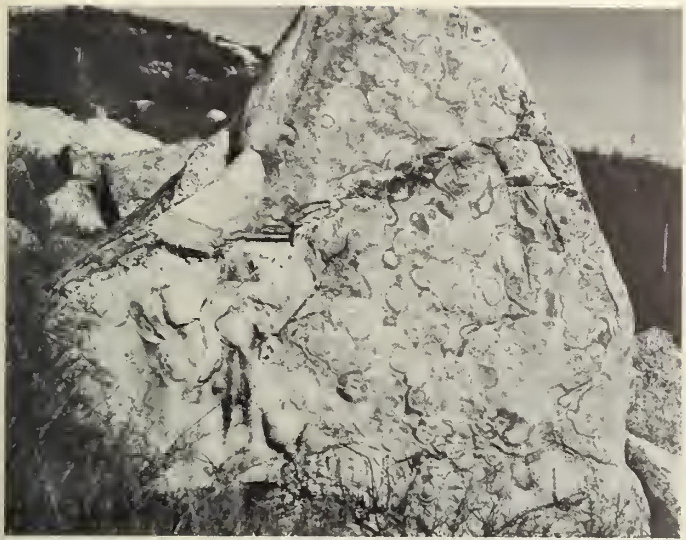

FIG. 16. Fine-grained granitoid rocks. Boulder with exposed face nearly parallel to garnet-rich layering. Unusual patterns formed by undulations in layers. South side of Hiriart Mountain.

in diameter from 0.1 millimeter to as much as 3 millimeters. Most crystals are salmon pink to brownish-red in color. They are particularly abundant in the line rock, but are also widely scattered through the other types of fine-grained, albite-rich pegmatite, and through graphic granite and other coarse-grained perthite-rich units. Their distribution appears to be regular only in the line rock. Many of these garnets are slightly altered, and are coated with stains of manganese oxide; where the alteration has been unusually intense, large masses of line rock are stained.

Spessartite is present also in the innermost pegmatite units as well-formed crystals as much as an inch in diameter. Some of these crystals are clear and free from cracks and other imperfections. Most of them, however, are marred by fractures and alteration, in general to a greater degree than the smaller crystals near the walls of the dikes. Most of the crystals with diameters greater than half an inch are so severely fractured that they crumble readily to a brown grit. In contrast, some pocket garnet occurs as flattened inclusions in muscovite, and is commonly pure and unaltered. These crystals are too small to be of use as gem material.

Grossularite (essonite), the calcium-aluminum garnet, is much less abundant in the Pala pegmatites than in those of the Ramona and other southern California districts. A manganesian variety occurs sparingly in the pocket-bearing parts of the Tourmaline King, Stewart, Douglass, and several dikes on Hiriart Mountain, chiefly as well-faced crystals $\frac{1}{16}$ inch to $\frac{1}{4}$ inch in diameter. These crystals are dodecahedrons and trapezohedrons of exceptionally attractive honey-yellow to orange-brown color. Most of them are attached to crystals of quartz or cleavelandite.

A manganese-bearing variety of andradite, the calcium-iron garnet, is a rare constituent of the border zones of several of the pegmatites adjacent to gabbroic country rock, and the mineral may have been derived in part from digested wallrock material. This garnet forms very small crystals of deep-red color, and is generally associated with biotite.

Tourmaline. Many varieties of tourmaline are present in the pegmatites. Schorl, the deep-black iron tourmaline, is the most abundant, forming both the characteristically striated prisms and columnar aggregates, or bundles of rodlike crystals. The mineral appears lustrous and black in hand specimen, blue to deep violet under the microscope. Some of the crystals are shattered and somewhat chalky, apparently in part because of alteration. Many are fractured, especially in a direction parallel to the base, and some of these fractures have been healed with quartz, albite, or aggregates of these minerals and mica. A few broken crystals of schorl have been recemented with finer-grained black tourmaline.

The schorl is most abundant in the upper parts of a given pegmatite, and the crystals generally increase in number and coarseness from the hanging-wall contact downward toward the horizon of the pocket zone. Exceptionally rich concentrations occur immediately above pockets in many dikes, and very coarse, well-formed crystals are present in most of the pockets themselves. The footwall parts of the pegmatites also contain this mineral chiefly as numerous small crystals that are rather uniformly scattered through the fine-grained, aplitic units. Such tourmaline-bearing granulite forms much of the lowermost part of the Stewart dike.

The schorl is scattered as pencil-like crystals through the perthite-rich pegmatite of the wall zones and outer intermediate zones of many dikes, and in places forms swarms of such crystals. Elsewhere the crystals are nearly parallel, and appear to have developed normal to contacts with the wallrock, to contacts between minerals, or to fractures. The schorl occurs also as sprays and rosettes, some of very large size. Several crude rosettes in the Stewart dike are 7 feet in diameter, and somewhat similar large radial aggregates are found in the Tourmaline King, Tourmaline Queen, and Pala Chief pegmatites. Most of the schorl is associated with muscovite, albite, and quartz, and commonly forms fine- to medium-grained aggregates that are interstitial to much coarser crystals or crystal groups of graphic granite, perthite, or, rarely, anhedral quartz. Graphic intergrowths of quartz and schorl are abundant in places, but rarely form masses greater than 6 inches in maximum dimension.

FIG. 17. Sharply layered line rock flanked on left by massive quartz with euhedral perthite and on right by fine-grained rock without prominent layering. Garnet-rich layers are irregular. South side of Hiriart Mountain.

Other varieties of tourmaline in the Pala pegmatites comprise the medium- to deep-blue indicolite, the pink to pale-red rubellite, the green emeralite, and the colorless achroite. Nearly all intermediate colors, tints, and shades occur also, with only the brown types not well represented. Two or more colors are commonly present in a single crystal, and either are disposed in random fashion or are arranged systematically. Some bicolored and multicolored crystals of prismatic habit are characterized by a concentric, or layerlike zoning with respect to their long axes. Deep-blue to black cores with single, double, or triple rims that are colorless, green, blue, or pink are most common, but many other combinations occur. ''Watermelon tourmaline'' is one attractive type in which an outer rim of green surrounds a colorless layer, and both these layers enclose a pink core. Some pink crystals of exceptional quality are veneered with a thin black or very dark-blue rim.

A different type of color zoning characterizes other crystals, which contain two or more contrasting layers that lie perpendicular or nearly perpendicular to their long axes. Many of these crystals are green on one end and pink on the other, and many others grade from black to green or pink, or even from black to colorless. Nearly all combinations are known, and some crystals show five or more alternations of colors in their length. More than one type of color zoning in a single crystal is not uncommon, especially where schorl is involved. The end of the crystal nearest the pegmatite wall is ordinarily black; the color changes to pink, green, or other alkali-bearing types as the crystal is traced toward its other end. The black material commonly persists farther in this direction in the interior of the crystal than in its outer parts, so that part of the crystal contains a black core and a lighter-colored rim. It should be emphasized that there are numerous exceptions to this generalization, and that many pink-cored crystals, for example, have deep blue or even black rims.

The colors in some zoned crystals are very sharply bounded from one another, whereas in others they appear to merge very gradually. In most of them, however, the colors intergrade within distances of 2 millimeters or less.

The crystals are rather consistently prismatic, and occur as isolated individuals, as columnar composites, as parallel or radiating groups, and as jackstrawlike aggregates. Some blue and pink aggregates of very fine-grained tourmaline form irregular masses in the pocket bearing parts of many pegmatites. They appear to be feltlike, and are very pure. Some crystals are so closely spaced that they form the principal constituent of the rock, but most of them represent less than 5 percent of the pegmatite unit in question. Individuals vary considerably in size, ranging from tiny needles to single prisms 6 inches in diameter and at least 4 feet long. Most of them are less than an inch in diameter and 4 inches long.

The crystals are commonly fresh and lustrous, and many are clear. The chief flaws are fractures, cavities, and inclusions, many of which are so small and closely spaced that they appear as a cloudiness or milkiness in the mineral. Some larger fractures are clearly healed with quartz or finer-grained aggregates of other tourmaline. Much of the tourmaline is opaque or otherwise of poor quality because of alteration, rather than the presence of mechanical imperfections. This alteration is most pronounced in the pink and colorless varieties, in which it causes a progressive decrease in hardness and toughness, loss of luster and transparency, and an increasingly clayey appearance. All stages of this alteration are well shown in the Stewart dike, especially in the underground workings of the Stewart and Gem Star mines.

A little of the schorl and nearly all of the other tourmaline occur in pocket pegmatite. They are most abundant in the central parts of the dikes, where they commonly form handsome crystals. They occur also in fracture fillings and fracture-controlled replacement bodies, especially in the upper parts of the thickest dikes. The rubellite is associated with quartz, cleavelandite, pocket perthite, muscovite, and especially with lepidolite. In the Stewart dike crystals of nearly fresh to thoroughly altered pink tourmaline form rosettes in fine-grained lepidolite, and this attractive lepidolite-tourmaline rock has been displayed in museums the world over.

FIG. 18. Line rock (top) adjacent to very coarse-grained aggregate of perthite and graphic granite. Note cleavage reflections from large crystals. At bottom is fine-grained quartz-albite-perthite-muscovite pegmatite with less sharply developed layering. South side of Hiriart Mountain.

The emeralite, or green tourmaline, is generally associated with quartz, cleavelandite, and other pocket minerals, and in many places occurs as inclusions in coarse books of muscovite. It is the most common alkali tourmaline in the fracture-filling and replacement units in perthite-rich pegmatite. The blue and colorless varieties are generally present in the pocket-bearing parts of the pegmatites, and are most abundant in and adjacent to concentrations of lepidolite.

Spodumene. Most of the spodumene in the Pala pegmatites has formed as very coarse, lath-shaped crystals. In general they are white to gray, and are opaque. Where fresh, they have a nearly pearly luster, but in most exposures they are sufficiently altered to appear dull and even earthy. Individual crystals are as much as 14 inches wide and 9 feet long, but the average dimensions are more nearly 3 inches and 2 feet, respectively. Few are thicker than 2 inches, and in most of them this dimension is less than 1 inch. They are deeply striated in a direction parallel to their elongation. Many crystals are twinned, with the twin planes parallel to their flat sides.

The coarse variety of spodumene almost everywhere occurs with quartz that is also very coarse grained, and aggregates of these two minerals are especially well developed in the Stewart, Pala Chief, and Vanderburg-Katerina dikes. Common associates are cleavelandite, muscovite, and lepidolite. Many of the spodumene crystals are thoroughly altered to white, gray, tan, or pink clay pseudomorphs. Much of the clay is halloysite, but some is montmorillonite and other species. There are all stages of alteration between nearly fresh spodumene and clay masses with no residuum of the original mineral.

A very small proportion of the spodumene is unaltered, and appears as attractive transparent crystals and crystal fragments. Much of this material is the pale pink to deep bluish-lilac variety kunzite, much is the colorless to yellowish triphane, and a little is the green hiddenite. Some of it is color-zoned, generally with lilac centers and colorless to green rims that are thicker at the ends of the crystals than along their sides. Most of the clear spodumene occurs as deeply etched cleavage fragments marked by striations and by triangular pits. These features have been described in detail by Schaller.[55] A little of the clear material forms complete or nearly complete crystals which are typically lathlike in the deposits on Chief Mountain, but are shorter and thicker in many of the deposits on Hiriart Mountain.

The kunzite, hiddenite, and triphane are plainly varieties of spodumene that escaped the alteration described above. Many specimens recently obtained from the Pala Chief and Katerina mines show clear spodumene as cleavage-bounded remnants within individual host crystals of partly altered spodumene. All these remnants have the same crystallographic orientation within a given host crystal, and there can be no doubt that they represent those parts of the crystal that were not altered.

Most of the clear spodumene fragments are less than 2 inches long, but there are some noteworthy exceptions. A few crystals of gem quality, recovered from the Pala Chief, Vanderburg, and Katerina mines, were at least 15 inches long and weighed 16 to 27 ounces. Several of them yielded flawless cut stones weighing 75 to 250 carats.

The gem spodumene occurs within the cores of the pegmatites, generally in a very coarse-grained quartz-spodumene unit. The unaltered or only partly altered crystals are most common along the margins of these innermost zones in at least two pegmatites, but in most others the quartz-spodumene unit is so thin that such details of distribution are of little practical significance. Most of the crystals, whether partly altered or not, are embedded in the quartz, or, locally, in aggregates of quartz, cleavelandite, and micas. The fragments of clear material are characteristically surrounded by white to deep-pink clay, some of which is stained black by manganese oxides. Most of the clay appears to have been derived from adjacent spodumene rather than from feldspars or other aluminum-bearing minerals.

Other Minerals

Beryllium Minerals. Several kinds of beryl (beryllium aluminum silicate) are present in the Pala pegmatites. Perhaps best known are the alkali-rich varieties in the pocket pegmatite of such dikes as the Tourmaline King, Tourmaline Queen, Pala Chief, Senpe, and Vanderburg-Katerina. They are the white to colorless goshenite and the pale-rose to peach-colored morganite. The crystals are equant to tabular, with sharply defined faces. They range from ¼ inch to 6 inches in maximum dimension, with an average of 2½ inches or slightly less. Many crystals are fairly simple tablets with small prism and broad basal faces, but most are marked by numerous modifying faces, some of which do not differ greatly in orientation from the base. Groups of complex crystals in parallel growth are common, and where the mineral is clear these aggregates are especially attractive. The white to pinkish beryl is generally associated with cleavelandite, muscovite, lepidolite, and quartz, and in places with spodumene and tourmaline.

Pale blue-green, moderately deep-blue, yellow-green, and golden beryl occurs in the quartz-rich cores of several pegmatites, chiefly as equant to prismatic crystals 3 inches or less in diameter. They are commonly well-formed, with sharply defined prism, pyramid, and basal faces, but some crystals are rough and subhedral. Most of them are milky or otherwise marred by inclusions and structural imperfections, but a few are clear. The subhedral crystals commonly appear sugary, owing to numerous closely spaced fractures. Some of the smaller, well-formed crystals are markedly chatoyant, and yield excellent cat's eye stones when cut.

This core beryl is not particularly abundant in any pegmatite, but is locally common in the central parts of the Stewart, El Molino, and several other dikes. It is generally associated with albite, and in places with muscovite. In the Katerina, El Molino, Pala Chief, and San Pedro mines it occurs with pinkish beryl, and a few crystals contain greenish cores and pinkish rims. The distribution of the colors suggests true crystallographic zoning.

Irregular masses of gray, yellow-green, and pale-green beryl, generally without obvious crystal form, are locally abundant in very coarse-grained units of the Stewart, San Pedro, and Vanderburg-Katerina pegmatites. In general this type of beryl is nearer the walls of the dikes than either of the types already described, and it is typically a constituent of quartz-blocky perthite intermediate zones. The crystals are as much as 14 inches in maximum dimension, although most are less than 5 inches. They are opaque, and ordinarily are marred by numerous fractures. Many of those that are gray or greenish gray are not easily distinguished from some types of quartz and feldspar in the pegmatites, although they have a characteristic greasy luster.

Still another variety of beryl is also anhedral, and occurs with graphic granite, muscovite, and locally with albite in the outermost parts of several pegmatites, notably the Stewart, Pala Chief, and El Molino. It is not abundant, although it is so difficult to recognize that it may well have escaped attention at many places. It forms irregular masses of white to medium-gray color which rarely exceed an inch in maximum dimension. So far as can be ascertained on the basis of refractive-index determinations and a few chemical analyses, this type of beryl contains the highest proportion of BeO and the lowest proportion of alkalies, as compared with other types in the pegmatites. The pocket beryl, in contrast, has the highest indices of refraction and contains the highest proportion of alkalies, notably sodium and caesium. The beryl

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[55] Schaller, W. T., Spodumene from San Diego County, California: California Univ., Dept. Geol. Sci., Bull., vol. 3, pp. 265-275, 1903.

formed in the cores and intermediate zones is intermediate in composition between these two extremes. The decrease in beryllium-oxide content of beryl from the walls of the dikes inward is compatible with the findings of geologists working in several pegmatite districts elsewhere in the United States.

Bavenite, a hydrous beryllium-calcium-aluminum silicate, forms clusters of small, radiating prismatic crystals, and is a very rare pocket constituent of the Pala Chief pegmatite. The crystals are white to colorless, and resemble those described from the Mesa Grande district by Schaller and Fairchild.[56] It is sporadically distributed on the sides and ends of beryl crystals, and also surrounds small ragged masses of beryl. Evidently it was derived from the beryl by alteration.

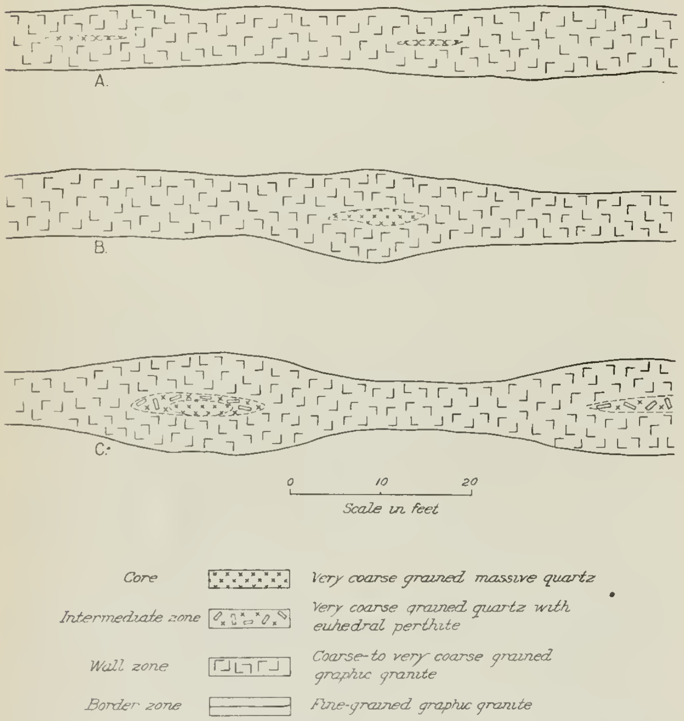

FIG. 19. Idealized sections of simply zoned pegmatite dikes in Pala district.

Small, tabular crystals of white to light-gray bertrandite, a hydrous beryllium silicate, show similar relations with respect to beryl. The bertrandite occurs in the Pala Chief and Katerina mines. In at least one specimen from the east end of the Pala Chief open cut, an aggregate of the crystals is a pseudomorph after a very small tablet of beryl, and elsewhere similar aggregates line cavities in corroded crystals of white to pink beryl. Most of the bertrandite crystals are less than 1 millimeter long.

Phenakite, beryllium silicate, is a rare constituent of the Vanderburg-Katerina dikes. It forms both flat, colorless crystals with sharply defined faces, and subhedral masses that are distinctly milky. It is associated with very small crystals of white to pale-blue topaz, and both minerals are attached to the exposed edges of large cleavelandite aggregates in the pocket pegmatite. None of the phenakite crystals exceeds $\frac{1}{2}$ inch in maximum dimension. Three tiny crystals of bertrandite were in a small cavity in one phenakite-cleavelandite specimen from the main workings of the Katerina mine.

Helvite, a silicate-sulfide of beryllium, manganese, iron, and zinc, is an exceedingly rare constituent of the pegmatite in the Gem Star and Katerina mines. It forms small, honey-colored tetrahedral crystals that are less than 1 millimeter in diameter. They occur on the surfaces of cleavelandite and spodumene crystals, and in general are typical of the pocket-bearing parts of the dikes.

Bismuth Minerals. Several bismuth minerals are present in the quartz-rich cores of pegmatites in all parts of the district, but constitute an almost negligible part of the pegmatite material as a whole. In the Stewart mine, an irregular mass of native bismuth weighing more than 100 pounds was encountered in the underground workings not far from the West adit. The principal associated minerals were quartz, spodumene, and amblygonite. According to Kunz,[57] the bismuth occurred as long, irregular crystals, and as platy crystalline masses as much as 12 or 15 millimeters long. One crystal an inch long was reported. Minor quantities of native bismuth occur also in the innermost zones of the Tourmaline King, Pala Chief, and Vanderburg-Katerina pegmatites, chiefly in association with quartz, albite, and lepidolite. It generally forms small scales and foils, which are typically pinkish to silvery on freshly broken surfaces.

Fibrous gray bismuthinite, bismuth sulfide, is associated with bismuth in the Stewart and Katerina mines, and with bismutite in the Pala Chief, Margarita, and El Molino workings. The bismuth and bismutite probably have been formed at least in part by alteration of the bismuthinite.

Bismite (bismuth oxide), pucherite (bismuth vanadate), and possibly a bismuth hydroxide form earthy, gray to yellowish-orange coatings on fractures in quartz, bismuth, and bismuthinite, especially in the Tourmaline King, Tourmaline Queen, Stewart, Pala Chief, and Vanderburg-Katerina pegmatites. Where individually recognizable the pucherite forms minute platy to needlelike crystals of gray to yellow-brown color. The bismite in some places has formed very small, tabular crystals, but in general occurs as a crystalline powder.

Bismutite, a bismuth carbonate, is probably the most widespread of the bismuth-bearing minerals. It fills fractures in bismuth and bismuthinite, and evidently was formed by the oxidation of these minerals. A few masses of bismutite contain cores of unaltered gray bismuthinite. The carbonate ranges in color from gray through canary yellow to pale orange yellow, and its luster is characteristically dull. It forms thin smears, veinlets, and some nodular masses as much as 2 inches in diameter, and is particularly widespread in the quartz-rich pegmatite of the Katerina mine.

Beyerite, a calcium-bismuth carbonate first described by Frondel,[58] forms gray-green to yellow-gray earthy coatings on fracture surfaces in the quartz of the Stewart and Katerina pegmatites. In many specimens it is intimately mixed with bismutite, and the two minerals are not readily distinguishable.

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[56] Schaller, W. T., and Fairchild, J. G., Bavenite, a beryllium mineral, pseudomorphous after beryl, from California: Am. Mineralogist, vol. 17, pp. 409-422, 1932.

[57] Kunz, G. F., Native bismuth and bismite from Pala, California: Am. Jour. Sci., 4th ser., vol. 16, pp. 398-399, 1903.

[58] Frondel, Clifford, Mineralogy of the oxides and carbonates of bismuth: Am. Mineralogist, vol. 28, pp. 532-533, 1943.

Clay Minerals. Clay minerals occur in all the Pala pegmatites, and appear to have been developed in two distinctly different ways. Minerals of the kaolinite group, formed by the weathering of feldspars, are widespread in the near-surface parts of the dikes. They coat feldspar crystals and fractures within them, and also fill larger, more continuous fractures that are traceable for several feet or even tens of feet along their strike. Some of this supergene clay is stained with iron oxides that presumably were derived from weathering of mafic minerals in the overlying gabbroic rocks. Much of this iron-stained clay has been mistaken by mineral collectors and even by some miners for the hypogene pocket clay that characteristically encloses the gem minerals in the pegmatites.

Several species of clay minerals in the pegmatites appear to be much older, and to have formed under hypogene conditions. This mode of origin is shown by the independence of their distribution with respect to the present surface, to postulated older erosion surfaces, to weathered and unweathered parts of the dikes, and to post-dike fractures. Moreover, they are associated with unaltered pyrite and other sulfide minerals, and consistently occur with tourmaline, cleavelandite, and other typical pocket minerals. These clays include representatives of both the montmorillonite and kaolinite groups, and have been discussed briefly by Ross and Hendricks.[59] Individual species thus far noted comprise endellite, halloysite, kaolinite, and montmorillonite.

To most of the miners in the district these minerals are known collectively as pocket clay. They are most abundant in the pocket-bearing parts of the dikes, where they commonly form the matrix in which the gem crystals occur. They are earthy to waxy where pure, but in most places are distinctly gritty because of numerous small, angular fragments of quartz and other minerals. They range in color from white and light-gray through yellowish and pinkish to raspberry red and bright reddish-brown. Most of the clay is distinctly pinkish, and some is marked by irregular white splotches. In places the clay minerals are stained along irregular fractures by manganese oxides.

Much of the white and pinkish clay occurs as pseudomorphs after spodumene. Also derived from spodumene are dense, butter-colored types of endellite and halloysite that are known locally as "turkey-fat clay." Pale to deep pink clay minerals also were formed by the alteration of tourmaline, and abundant pink to brownish clays by the alteration of feldspars. Not only do they form pseudomorphs after these minerals where alteration has been complete, but they occur in fractures and shear zones that transect partly altered crystals, as well as large masses of the pegmatite itself. These clays also line cavities formed by the selective corrosion and solution of the quartz rods in graphic granite.

Columbium-Tantalum Minerals. Members of the columbite-tantalite series (iron-manganese columbate-tantalate) are widespread minor constituents of the pegmatites, and are locally abundant in the central parts of the Stewart and Vanderburg-Katerina dikes. Most common is ferrocolumbite, in which the iron :manganese ratio is greater than 4:1 and the columbium :tantalum ratio is greater than 3:1. This mineral forms tabular crystals, generally no more than ¼ inch thick and 1 inch by 1 inch in plan. The principal faces of most of the crystals are flat, but some very thin and broad crystals are markedly curved. Many of these platy individuals are $\frac{1}{16}$ inch or less in thickness and as much as 4 inches in maximum dimension. They commonly occur in radiating groups. A few crystals are more equant, and appear as subhedral to euhedral "chunks" ½ inch to 6 inches in diameter, with an average of about an inch.

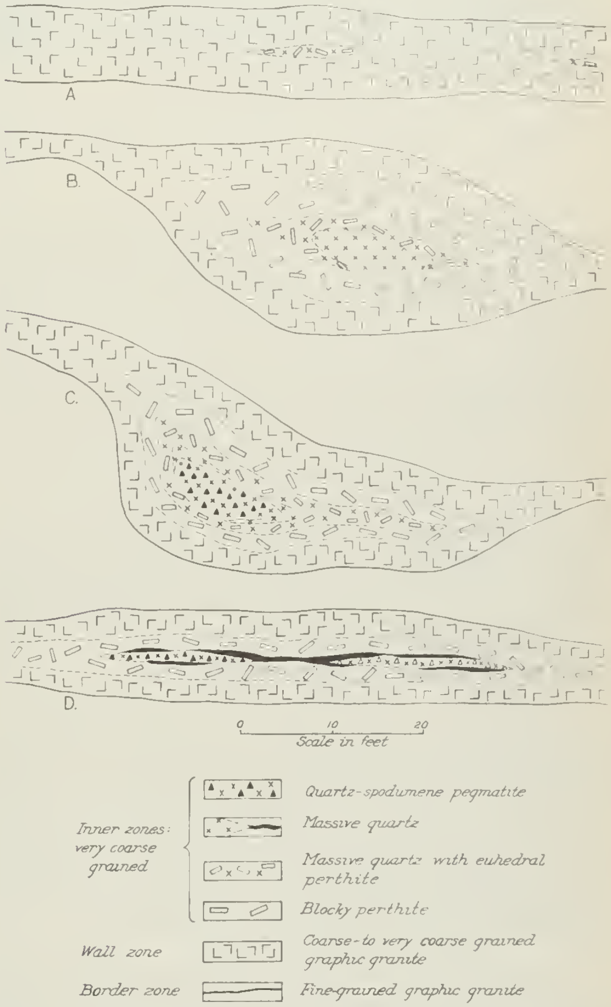

FIG. 20. Idealized sections of pegmatite dikes in the Pala district, showing typical relations of intermediate zones and cores.

The columbite is dull black on crystal faces, but has a bright submetallic luster on freshly broken surfaces. In contrast to this is manganotantalite, a closely associated species found in the Katerina and very sparingly in several other mines. This mineral forms rather thickly tabular crystals with slightly brownish outer surfaces and a distinctly resinous, splintery appearance on freshly broken surfaces. It is very rich in manganese, and has a high ratio of tantalum to columbium.

Both the columbite and the manganotantalite are in the cores and other inner units of the pegmatites. They are characteristically associated with quartz, less commonly with cleavelandite and sugary albite. Many of them are coated with fine flakes and scales of yellowish muscovite.

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[59] Ross, C. S., and Hendricks, S. B., Minerals of the montmorillonite group: U. S. Geol. Survey Prof. Paper 205-B, pp. 25-28, 34, 69-70, 1945.

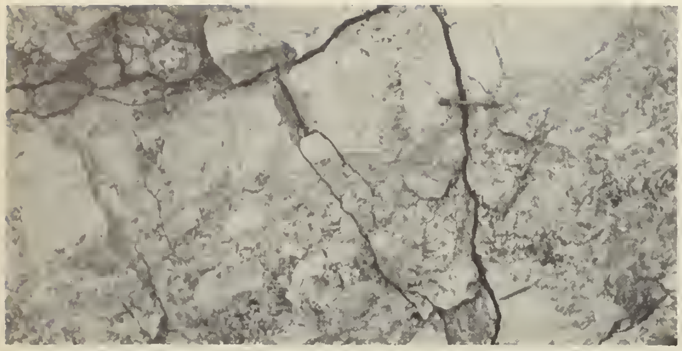

FIG. 21. Quartz-spodumene pegmatite in wall and back of large room, Stewart mine. This unit is overlain by massive quartz (dark, at top), and is underlain by quartz-cleavelandite-perthite-muscovite pegmatite (at top and below level of man's head). Massive lepidolite ore at lower right.

Two crystals of stibiotantalite, antimony tantalate-columbate, were observed in the Katerina mine, where they were in close association with coarse-grained cleavelandite, quartz, orthoclase, and colorless to pinkish beryl. The crystals were near several clusters of manganotantalite tablets, which they resembled in color and luster. In contrast, however, the antimony mineral showed a perfect cleavage. Numerous other brownish crystals of tantalum-bearing minerals were tested for antimony, but all were found to be ordinary manganotantalite.

Small crystals of pale honey-yellow to very dark microlite, essentially a tantalate of calcium, are present in pocket aggregates of quartz, lepidolite, muscovite, albite, and tourmaline, but are known from only two pegmatites, the Tourmaline King and the Stewart. The crystals are octahedral and dodecahedral, with maximum dimensions that rarely exceed 1/16 inch.

Lithia Micas. In addition to muscovite, biotite, and lepidolite the pegmatites also contain cookeite, hydrous lithium-aluminum silicate. It is a rather widespread pocket species, and ordinarily forms a coating on crystals and crystal aggregates of quartz, lepidolite, spodumene, albite, and orthoclase. It forms white, buff-colored, and very pale pink aggregates of small plates and flakes. It is most common in some of the gem-bearing parts of the Tourmaline King, Tourmaline Queen, Stewart, Pala Chief, and Vanderburg-Katerina dikes.

Zinnwaldite, the lithium-iron mica, is very sparingly present in several pegmatites as dark-gray to deep reddish brown crystals and flakes. It resembles phlogopite in having a bronzelike luster. Most of the crystals are stubby prisms ¼ inch in maximum length. They are only in the pocket-bearing parts of the pegmatites, where they are most commonly associated with quartz, cleavelandite, and beryl.

Phosphate Minerals. Amblygonite, lithium-aluminum fluo-phosphate, is a common constituent of the spodumene-bearing pegmatites, especially those on Hiriart Mountain and in the south part of the Stewart dike. Ordinarily it forms subhedral to anhedral crystals ½ inch to at least 18 inches in diameter. Larger individuals commonly appear as subrounded or nodular masses. Many crystals are single, but others are grouped in ovoid to discoidal aggregates several feet or even tens of feet in diameter. The largest of these aggregates, encountered in the underground workings of the Stewart mine, was nearly 40 feet long, 2 to 15 feet wide, and 16 feet in maximum thickness. This was exceptional, however, and few of the other aggregates in the district exceed 3 feet in maximum dimension.

Most of the amblygonite is white and bluish white, and has a typical pearly luster. Cleavage surfaces of the coarse crystals are broadly curved, and in many places are markedly uneven in detail. Most of the masses are cut by irregular networks of fractures and zones of shattering that are 1/32 inch to ¼ inch wide. The broken material is "healed" with fine-grained, sugary amblygonite of pale green to pale blue color. Both individual crystals and the larger crystal aggregates typically occur in massive quartz, but are also associated with albite, lepidolite, muscovite, and spodumene. In a few dikes the amblygonite is in readily distinguishable zones of very coarse-grained pegmatite, composed of quartz and some spodumene. These units characteristically occur along the outer margins of quartz cores, or of quartz-spodumene cores.

Associated with the spodumene and amblygonite in the inner parts of many pegmatites are lithiophilite, lithium-manganese phosphate, and triphylite, lithium-iron phosphate. These minerals form equant to thickly tabular crystals with rough but well-defined faces. They occur both singly and in clusters of as many as a dozen crystals. Most of them are so stained by manganese oxides that they appear as black blotches on the walls of the mine workings, and in this respect they resemble the spessartite garnet so common in many other pegmatite districts.

Individual crystals are ¼ inch to 17 inches in maximum dimension, with an average of about 4 inches in the pegmatites where they are most abundant. Where fresh, the triphylite is bluish gray, and the much more abundant lithiophilite ranges from flesh colored through pinkish tan to light reddish-brown. Unaltered and only partly altered lithiophilite is fairly abundant, especially in the Stewart dike, but nearly all the triphylite in the pegmatites has been converted to other, secondary phosphate minerals.

The lithiophilite and triphylite are most common in the outer parts of the quartz-spodumene zones and quartz-spodumene-amblygonite zones, and in the inner parts of adjacent perthite-bearing zones of very coarse grain size. They are well exposed in the backs of several drifts and stopes in the Stewart mine, where they occur chiefly in coarse quartz-perthite pegmatite. Although this particular unit lies 5 feet to 20 feet or more above the lepidolite-rich rock that was mined, successive rock falls in some of the larger openings during the past two decades have revealed the presence of these phosphate minerals in greater quantities than were apparent during the periods of active operations. Lithiophilite is far more abundant than triphylite in the pegmatites on Queen and Hiriart Mountains, but triphylite may be dominant in the Pala Chief and in at least one other dike on Chief Mountain. Both minerals occur sparingly as small crystals in the central parts of a few dikes that do not appear to contain spodumene or amblygonite. Chief among these dikes are the Tourmaline King, White Cloud, and Tourmaline Queen.

Of particular interest to mineralogists is a group of rare manganese and iron phosphate minerals in several of the pegmatites, notably the Stewart, Pala Chief, and Vanderburg-Katerina. Most of these minerals were formed directly or indirectly from lithiophilite and triphylite, and pseudomorphs, fracture-filling relations, and other evidence of their secondary origin are widespread. Progressive alteration of the two primary minerals first yielded sicklerite, iron-manganese-lithium phosphate, and then, accompanied by loss of lithium, yielded purpurite and heterosite, iron-manganese phosphates. Hydration of the lithiophilite and triphylite, and locally of the sicklerite, resulted in development of stewartite, hureaulite, and palaite[60] (hydrous manganese phosphates), salmonsite (hydrous iron-manganese phosphate), and strengite (hydrous iron phosphate). At least one dark-brown to black iron-manganese phosphate mineral also is present, but it has not as yet been specifically identified.

Many crystals of lithiophilite and triphylite have been altered concentrically, so that cores of residual primary material are surrounded by successive layers of the minerals derived from them. Similar relations have been described from other phosphate-bearing pegmatites, notably the Varuträsk pegmatite near Boliden, Sweden,[61] and several pegmatites in the Black Hills region of South Dakota.[62] The unaltered masses of lithiophilite and triphylite are commonly surrounded by a layer of dark reddish-brown sicklerite that ranges in thickness from a knife edge to nearly an inch. Cleavage surfaces of these minerals are continuous. In places, however, the two minerals are separated by stringers and thin lenses of buff-colored, pale amber, or reddish-brown hureaulite, which forms finely crystalline aggregates that are veined and corroded by the sicklerite. Fringing the relatively dark-colored sicklerite layer in most crystals is a somewhat thicker layer of buff to yellowish-brown salmonsite. This mineral forms cleavable masses with rather dull luster, and is typically transected by thin and continuous veinlets of finely crystalline, white to flesh-colored palaite (hureaulite). These veinlets transect also the sicklerite, lithiophilite, and triphylite. Most of the hureaulite is evidently an alteration product of lithiophilite.

Aggregates of blue, lilac, rose-red, and purple strengite,[63] purpurite, and heterosite are scattered through the salmonsite layers and in the dark, oxide-stained material beyond. Individual crystals are very small, but the aggregates themselves commonly are one-quarter inch to three-quarter inch in maximum dimension. Most of them are ovoid, but some are thinly tabular, and fill cracks in the salmonsite, sicklerite, and earlier phosphate minerals. They are themselves transected by stringers of palaite (hureaulite). Stewartite is present in all the other minerals, chiefly as canary-yellow films and aggregates of tiny crystals. Relatively coarse fibers, some as much as 0.5 mm. long, occur in the layers and pods of purpurite and strengite, and are locally abundant. The mineral is most abundant, however, where it occurs in lithiophilite as fracture fillings. It is intimately intermingled with other species, especially hureaulite, lithiophilite, and salmonsite, and is one of the most widespread of the secondary phosphate minerals.

Triplite, a fluo-phosphate of iron and manganese, occurs sparingly in the Stewart and Vanderburg-Katerina pegmatites, where it is associated with lithiophilite and triphylite. Like these minerals, it forms crystals with rough faces. The crystals are ¼ inch to 5 inches in diameter, with an average of about an inch. The mineral occurs also as tabular, fracture-filling masses within quartz, and rarely within coarse quartz-spodumene or quartz-perthite varieties of pegmatite. It is deep-tan to dark reddish-brown on freshly broken surfaces, and has a resinous luster. Cleavage is fairly well developed. Most crystals are heavily stained with manganese oxides, and many are coated with a blue-gray film of very finely crystalline vivianite, hydrous ferrous phosphate. The vivianite appears to have been derived from the triplite crystals.

Monazite, a phosphate of the rare-earth minerals, is widespread but not at all abundant in the pegmatites. It occurs as small, equidimensional grains, and as tabular crystals of cinnamon-brown color, chiefly in line rock and other albite-rich units. Well-formed crystals ½ inch in maximum diameter are scattered very sparingly through cleavelandite-bearing pocket pegmatite in the Katerina mine. Most of the crystals, however, are subhedral to anhedral, and are much smaller.

Small crystals of pale-pink, violet, and purple apatite, essentially a calcium phosphate, are rare constituents of the pockets, and also occur in albite-bearing parts of perthite-rich pegmatite in several of the dikes on Queen and Hiriart Mountains. Some short, well-formed prismatic crystals in the Pala View mine are ¼ inch to 1½ inches long, but in most places they are less than ¼ inch long. Many of the apatite crystals are tabular, and are flattened parallel to the base.

Sulfide Minerals. Sulfide minerals occur sporadically in several pegmatites. They are present chiefly along fractures in cores and other inner zones. Some are disseminated as small crystals, mainly in quartz. Many of the sulfide minerals in the near-surface parts of the pegmatites have been oxidized, and only stains of iron oxide or other secondary products testify to their former presence. The sulfide species are probably much more abundant at depth.

Arsenopyrite, iron sulfarsenide, forms fine-grained aggregates of silvery gray color, mainly in quartz and albite of the inner zones. Bismuthinite, already mentioned in the discussion of bismuth minerals, is most abundant in the Stewart and Katerina mines, but occurs in all parts of the district. Bornite, copper-iron sulfide, forms typically iridescent stains on fracture surfaces in the Tourmaline Queen, Stewart, Douglass, and San Pedro pegmatites, and especially in the El Molino pegmatite. It occurs also as small, rounded masses in quartz and albite. Chalcocite, copper sulfide, forms sooty black masses the size of a pea in the quartz-rich inner parts of the El Molino and Stewart pegmatites. It is typically associated with thin films of malachite and chrysocolla.

Pyrite is widespread as cubes ⅛ inch or less across, and as fine-grained crystalline aggregates about an inch in maximum dimension. It occurs in quartz veinlets and in quartz-rich inner zones, where it forms yellowish- to greenish-gray aggregates. Most of the mineral, however,

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[60] According to W. T. Schaller (personal communication), x-ray studies during recent years have demonstrated that palaite and hureaulite are identical.

[61] Quensel, P., Minerals of the Varuträsk pegmatite. 1. The lithium-manganese phosphates: Geol. fören. Stockholm Förh., vol. 59, pp. 77-96, 1937.

Mason, Brian, Minerals of the Varuträsk pegmatite. 23. Some iron-manganese phosphate minerals and their alteration products: Geol. fören. Stockholm Förh., vol. 63, pp. 134-155, 165-175, 1941.

[62] Fisher, D. J., Preliminary report on the mineralogy of some pegmatites near Custer: South Dakota Geol. Survey Rept. Inv. No. 50, esp. pp. 43-47, 1945.

[63] Some of the material previously identified as strengite may well be phosphosiderite. See Murdoch, Joseph, Minerals of California—Supplement No. 1 to Bulletin 136: California Jour. Mines and Geology, vol. 45, p. 529, 1949.

is partly oxidized where now exposed, and hence is dull brown in color. Pyrite occurs also in book muscovite as waferlike inclusions with square outline. Most of them are $\frac{3}{16}$ inch in maximum dimension.

Molybdenite, molybdenum sulfide, forms tiny flattened crystals in the quartz of very coarse-grained pegmatite that forms the inner zones of the Pala Chief, San Pedro, Vanderburg-Katerina, and El Molino dikes.

Zeolites. The zeolite minerals heulandite, laumontite, and stilbite are widespread but minor constituents of fracture fillings and of pockets and other replacement units in the pegmatites. All are hydrous sodium-calcium-aluminum silicates, and are most commonly associated with the clay minerals of the inner pegmatite units. Heulandite forms buff to light-brown tabular crystals 2 mm. in maximum dimension. It generally occurs with stilbite, which forms lighter-colored aggregates of small, platy crystals. The laumontite is present as rosettes and sprays of white, thinly columnar crystals, few of which are longer than 1 mm. This mineral is characteristically associated with stilbite and clay minerals, and in places appears to have been formed by the alteration of stilbite.

Rare Accessory Minerals. Andalusite, aluminum silicate, forms masses as much as 3 inches in diameter in several pegmatites exposed in the north parts of Queen and Chief Mountains. The mineral is pale pinkish to flesh colored where fresh, and has a characteristic greasy to dull pearly luster. It occurs in the outer parts of the pegmatites, and may have been formed as a result of action between pegmatite solutions and aluminum-rich wallrock.

Cassiterite, tin oxide, is a very rare constituent of several pegmatites exposed on Hiriart Mountain. It forms crystals $\frac{1}{8}$ inch or less in diameter in the pocket-bearing parts of these dikes, where it is associated with coarse cleavelandite and small crystals of topaz. These crystals are a deep reddish-brown. Most of them are formed on cleavelandite crystals that line small, irregular cavities.

Epidote is locally abundant near the walls of several pegmatites, and is associated with garnet and biotite. It is pale to deep grassy-green in color, and forms stubby to rodlike crystals that are highly fractured. It may have been derived in part from wallrock material.

Loellingite, iron diarsenide, forms massive crystalline platy aggregates, many of which are curved, and occur in groups of layerlike shells, some of which are interlayered with quartz. The mineral is silvery where fresh. Loellingite is mainly in the cores and inner parts of adjacent intermediate zones, and commonly is in or near masses of lithium-manganese-iron phosphate minerals.

Petalite, lithium-aluminum silicate, forms white cleavable masses with pearly luster in the Stewart, Vanderburg-Katerina, and Anita pegmatites. Few of the crystals exceed an inch in maximum dimension. They occur chiefly with spodumene, but are associated also with albite and lepidolite, and in general are rather rare.

Pollucite, hydrous caesium-aluminum silicate, has been reported from the Pala district, but probably is very rare. In general this mineral closely resembles quartz, and is found in colorless to milky aggregates that are much fractured.

Several varieties of spinel are rare constituents of the dikes. Small octahedrons of blue and deep-green gahnite, zinc aluminate are along fractures in the quartz of the innermost pegmatite units in the Tourmaline King and Vanderburg mines. In some places they are associated with columbite-tantalite. The mineral occurs sparingly in line rock, especially in the garnet-rich types on Hiriart Mountain.

Hercynite, iron aluminate, forms rare tiny black to very deep blue crystals in the outer zones of several pegmatites; some crystals of slightly lighter color occur in the inner zones, where they are associated with cassiterite. Pleonaste, magnesium-iron aluminate, forms small, lustrous octahedrons of very dark green to black color. Like the hercynite, it is chiefly in the outer zones of the pegmatites. Both these minerals may well be the product of reactions between pegmatite solutions and wallrock.

Some minerals in the pegmatites are not accessory constituents, according to the strictest definitions, but have been derived from one or more other minerals by alteration. Among these alteration minerals are sericite, manganite and psilomelane, hematite and goethite, opal, and chalcedony. In general these minerals coat crystals and grains of older minerals, and also fill numerous fractures and cleavage cracks in them.

Paragenetic Sequence of Minerals

Despite numerous irregularities of detail, the paragenetic sequence of minerals in the Pala pegmatites seems to be nearly uniform throughout the district. Earliest to form were the minerals indigenous to the outer zones. They comprise very abundant perthite and quartz, sparse garnet and beryl, and small but widespread quantities of muscovite, biotite, and schorl. The last three minerals are common also along fracture surfaces, and so may be in part younger than the others. Such species as garnet and biotite may well have been derived in places through reaction between pegmatite solutions and country-rock material, elsewhere by crystallization from ''uncontaminated'' pegmatite solutions.

As the minerals formed, they were corroded by solutions with which they were no longer in equilibrium, and were veined and surrounded by minerals deposited from these solutions. Many were fractured, and the fractures were filled with other minerals. Corrosion and replacement of earlier-formed constituents were widespread and locally very significant processes, and in places resulted in obliteration of numerous crystals of the earlier minerals. Such processes, and particularly the corrosion, took place over an appreciable range of time, beginning not long after the original crystallization of a given mineral. This was especially true during the formation of the inner pegmatite zones, when several minerals in addition to those not characteristic of the outer zones were formed.

During development of many inner zones, perthite, albite, and schorl were formed in abundance. Much spodumene was developed in some pegmatites, not uncommonly in association with amblygonite and other lithium-bearing phosphate minerals. Parts of some inner zones plainly were extended as apophyses into outer units, particularly during the later stages of pegmatite formation. With subsequent development of typical pocket-bearing pegmatite, the minerals of the inner zones were joined by numerous accessory species, including several that appear to have been formed in very small quantities. Aggregates of these minerals fill fractures in earlier zonal units, and also form replacement masses in these units. They reflect to an even greater degree than before the continued corrosion and replacement of earlier minerals by later constituents, and perhaps are products formed by deuteric processes late in the history of the dikes.

The fine-grained granitoid units, with their relatively simple mineralogy, cut across parts of the zones, but seem to be older than the typical pocket-bearing material. They appear to be superimposed on the pattern of some zonal units, both in a broad way and in detail, but are themselves transected by aggregates of typical pocket minerals. The age relations of these rocks are complicated in most places by the widespread later graphic granite and other mineral aggregates like those in the early-formed pegmatite units. Many of the dikes that contain appreciable quantities of the fine-grained granitoid rocks are clearly composites, with masses of graphic granite that cut both the fine-grained material and older graphic granite. Quartz, albite, muscovite, and garnet are the most abundant constituents of the fine-grained rocks, and with them in many places are schorl, biotite, and scattered rare accessory constituents.

The general age relations of the principal minerals in the pegmatites are summarized in table 4. The range of hypogene mineral development has been somewhat arbitrarily divided into four principal categories, or stages. The first encompasses a part of the primary consolidation of the dikes, and includes formation of border zones and wall zones. In some dikes it includes also the development of minerals in part from assimilated wallrock material. The second stage involves near-completion of primary consolidation, with progressive increase in the amount of reaction between crystallized pegmatite material and residual solutions. During this stage the inner zones of the dikes were formed, and some fracture fillings and replacements bodies were developed in the outer zones.

The pocket-bearing varieties of pegmatite were formed later, in part at the expense of pre-existing pegmatite of the inner zones. Although most aggregates of pocket material are in the central parts of the dikes, some are fracture-related layers, lenses, and networks in the outer units. The fine-grained albite-rich rocks that are common in the footwall parts of the dikes also contain pocket aggregates.

Table 4. General age-abundance relations of principal minerals in the Pala pegmatites.

Mineral	Stages [a]			
	Development of outer zones	Development of inner zones and formation of contemporary fracture fillings and replacement units in outer zones	Formation of line rock and associated fine-grained types	Formation of pockets and contemporary fracture fillings
Microcline	Very abundant	Very abundant		Sparse
Orthoclase		Abundant		Abundant
Quartz	Abundant	Very abundant	Very abundant	Very abundant
Albite	Common	Abundant	Very abundant	Very abundant
Muscovite	Sparse	Abundant	Abundant	Abundant
Biotite	Sparse	Rare	Sparse	
Lepidolite		Rare		Abundant
Garnet	Sparse	Sparse	Abundant	Sparse
Schorl	Sparse	Abundant	Common	Abundant
Alkali tourmaline		Rare		Abundant
Spodumene		Abundant		Common
Beryl	Sparse	Common		Common
Bismuth minerals [b]		Sparse		Sparse
Clay minerals		Rare		Abundant
Columbite-tantalite		Sparse		Sparse
Lithium-phosphate minerals [b]		Common		
Sulfide minerals		Sparse		Sparse
Zeolites				Sparse

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[a] The four stages are listed from left to right in general order of decreasing age, but there is much overlap and a few rock types constitute exceptions to the order. Some varieties of pocket-bearing pegmatite, for example, can be classed with the inner zones, in terms of occurrence and probable genesis. The relative age of line rock is known with certainty in few pegmatites.

[b] Represented in part by alteration products.

The generalizations noted above, though not intended to be complete, are based upon detailed field and microscopic analyses of intermineral relations. Three general criteria for establishing age differences were used. They involve the occurrence of a mineral: (1) as a pseudomorph, where the former existence and identity of the earlier mineral can be clearly established by means of residual material, crystal form, cleavage patterns, or some other characteristic; (2) as a filling of fractures or cleavage cracks in an earlier mineral or mineral aggregate; or (3) consistently in a pegmatite unit whose age relations are known.

The criteria of irregular mineral boundaries and the occurrence of euhedral crystals of one mineral in or against crystals of another have not proved very useful in the present investigations, as they generally permit two or more reasonable but contradictory interpretations. Of somewhat greater value are such features as the occurrence of a given mineral (a) along contacts between other minerals, (b) as inclusions oriented along cleavage directions in the host mineral, (c) as embayments or other forms that indicate the corrosion of an earlier mineral, or (d) in or consistently with another mineral whose age relations are known. These relations are not wholly diagnostic, and must be interpreted with care. In general, however, they have been helpful when used in combination with one another and with the criteria noted above.

Fig. 22. Graphic granite underlain by very coarse-grained perthite-quartz pegmatite, El Molino mine. Separating these two units is 18 inches of finer-grained pegmatite composed of abundant masses of graphic granite in a matrix of quartz, albite, and muscovite.

Origin of the Pegmatites

The Pala pegmatites do not appear to be closely related either in time or in space, to any nearby igneous rocks now exposed. They are truly granitic in composition, whereas all the large masses of intrusive rocks in the area range from gabbro to granodiorite. Moreover, the pegmatites are distinctly younger than all these rocks, and even transect aplitic dikes that are related to the granodiorite. On the other hand, the pegmatites are of the same general age as these batholithic rocks, as all are late Mesozoic and are overlain by sedimentary rocks of Upper Cretaceous age. Despite the apparent lack of close genetic relation at the present surface, the pegmatites are thought to represent a closing stage in the consolidation of the southern California batholith, and therefore to constitute late injections of still fluid material into already crystallized units of this huge composite mass. Probably the dikes represent end products of prolonged differentiation of the batholithic magma. A well-defined sequence that ranges from early basic rocks to later granodioritic rocks is present, but there appears to be a gap in the exposed record between the granodioritic rocks and the granitic rocks represented by the pegmatites.

The pegmatite dikes in the Pala district were emplaced probably along a set of subparallel fractures, as indicated by their attitude and by the existence in the district of numerous unfilled fractures with the same general orientation. The dikes appear to have been injected as liquid material and to have crystallized essentially as simple fracture fillings, rather than to have been formed, wholly or in appreciable part, by replacement of the country rock. This is attested by several features. The walls of the dikes are remarkably straight, and can be traced across contacts between different types of country rock without change in attitude. The dikes themselves show no changes in composition, thickness, or internal structure that can be correlated with changes in the wall-rock lithology. Moreover, the pegmatite fluid that was first injected must have pushed aside the country rock, as shown by irregular distortion and tight crumpling of schist and other relatively thinly foliated types of wall-rock in several mines. Finally, the disposition and structure of the pegmatite zones indicates that these units developed from the walls of the dikes inward, a sequence that is not compatible with development through replacement of country rock.

The postemplacement history of the pegmatites is much less readily determined, not so much for lack of evidence as for an abundance of evidence that appears to be partly in conflict when applied to a single hypothesis of origin. Schaller,[64] who devoted much attention to this general question, suggested that the dikes were once simple injections of magma that yielded an orthoclase rock, that at some later time they were solid graphic granite composed essentially of only microcline and quartz, and that all the other minerals now present were introduced still later and are the result of replacement processes. Certainly the widespread evidence of both corrosion and replacement of some minerals by others, particularly in the inner parts of the pegmatites, is striking testimony to a rather complex history of development.

As pointed out by Schaller,[65] the graphic granite is the oldest rock unit now present in the pegmatites, and at least its feldspathic part probably crystallized directly from the injected pegmatite magma. Not only the graphic granite, but also the younger zonal constituents—chiefly coarse-grained perthite, quartz, spodumene, and lithium phosphate minerals—were formed probably in this way. The layering or concentricity of the zones of graphic granite and other very coarse grained pegmatite may be the result of fractional crystallization from the walls of

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[64] Schaller, W. T., The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., vol. 10, p. 276, 1925.

[65] Schaller, W. T., op. cit., p. 276, 1925.

the dikes inward. Such an origin for zones in pegmatites has been discussed at length by Cameron, Jahns, McNair, and Page.[66] Fracture-filling apophyses projecting from inner zones into zones nearer the pegmatite walls establish clearly the age relations of the zones. The reverse relation has not been observed. As traced inward from the walls of the dikes, the zones show consistent changes in mineralogy and texture, changes that apply even to variations in the properties of single mineral species, such as beryl and albite. The mineralogic and textural sequences are consistent from dike to dike throughout the district, although few dikes show all members of the sequence.

There is no evidence that the various units of graphic granite or other very coarse-grained pegmatite have formed at the expense of any pre-existing pegmatite. Careful and extended search has failed to reveal even traces of material that might be assigned to an earlier sequence of pegmatite units. Although such evidence is negative, it is so abundant that it cannot be ignored, particularly in view of the evidence for the replacement origin of much pegmatite matter other than that of the zones.

The pocket-bearing pegmatite evidently was derived in part at the expense of pre-existing zonal material, as shown by widespread pseudomorphism and fracture-guided corrosion. Quartz and potash feldspar were strongly corroded, and in places the quartz rods were selectively dissolved out of graphic granite. It is difficult to determine with confidence whether the pocket minerals were formed by solutions at least partly from sources outside the dikes, or whether they are the final products of pegmatite consolidation, either in place or derived from other parts of the dikes. Certain it is that the progressive accumulation and late stage crystallization of mineralizing fluids during consolidation of the dikes could explain many, if not all of the relations in the central parts of the complex pegmatites.

In most of the dikes the proportion of material formed at the expense of other pegmatite is not large. In a few, however, the volume of this type of material is great, and it seems likely that the material was formed partly from solutions derived from other places in the dike, or even from sources farther removed. Excellent examples are the large, lepidolite-rich masses in the Stewart pegmatite. These masses contain abundant and widespread residua of quartz, spodumene, and amblygonite that represent quartz-spodumene and massive quartz zones that once were much more extensive. The lepidolite-rich pegmatite locally transgresses zonal boundaries, and in detail the lepidolite plainly was formed at the expense of older mineral crystals much larger than their present remnants.

Whatever explanation is suggested for the origin of the pocket pegmatite and other material that is at least in part of replacement origin, the structural relations of these units are fairly plain. Both occur chiefly in the central parts of the dikes, where they are typically much less regular in shape and attitude than the zones. Some of these units, however, are nearer the dike walls, where they are generally controlled in their distribution by one or more sets of fractures.

Perhaps the most puzzling of all the pegmatite units, so far as genesis is concerned, are the fine-grained granitoid rocks. The line rock, for example, has been interpreted by Waring [67] as an early product of simple crystallization from a "hydrous magma," by Merriam [68] as the product of rhythmic replacement in an early, probably primary aplite, and by Schaller [69] as a much later result of replacement of pre-existing graphic granite by soda-rich solutions. The fine-grained, albite-rich rocks are clearly younger than some graphic granite, but are older than the stringers, lenses, and small pods of later graphic granite in them. Wherever the line rock or associated aplitic material is in contact with the main masses of graphic granite that constitute much of a given dike, and the age relations of the rocks can be determined, the graphic granite is the older of the two. On the other hand, the pocket pegmatite is distinctly younger than some aplitic units, as offshoots from masses of such pegmatite transect these finer-grained rocks.

The fine-grained granitoid rocks form masses whose shape and distribution generally do not conform to the structure of the pegmatite zones. The zonal structure is the older, and the fine-grained units appear to have been superimposed upon it, particularly in its footwall parts; they cut across the ends of the concentric units in the bulges of some irregular dikes, and are not oriented in accord with the zonal structure of many other dikes. These features, together with the occurrences of graphic granite residual in the line rock and associated fine-grained types, may mean that many, if not all, of these rocks were derived from graphic granite by replacement processes. Schaller [70] has accumulated widespread evidence for the existence in these rocks of not only graphic granite residua, but unreplaced aggregates of quartz rods in a matrix of sugary albite, quartz, and muscovite. Evidence thus far obtained during the present investigations does not seem to warrant definite conclusions, but if Schaller's views are correct, the fine-grained granitoid rocks must have been formed prior to the development of the pocket pegmatite in the dikes, presumably by solutions introduced from sources at considerable distances from the areas of replacement.

ECONOMIC FEATURES OF THE PEGMATITE MINERALS

Lithium Minerals

Lepidolite

Lepidolite was once used mainly as a source of lithium salts, but during the past three decades the ceramic industry has absorbed the bulk of domestic production. The mineral is used directly in the manufacture of glass, as it not only is an excellent fluxing material, but it increases the luster, weather resistance, electrical resistance, and strength of the product. More important, it reduces the coefficient of expansion, thus making the glass more resistant to thermal shock. Lithium glasses are in great demand for high-pressure gages, electronic tubes, and other devices subject to mechanical stresses or sudden temperature changes. Lepidolite is also an ingredient of

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[66] Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., The internal structure of granitic pegmatites: Econ. Geology, Mon. 2, pp. 97-105, 1949.

[67] Waring, G. A., The pegmatyte veins of Pala, San Diego County: Am. Geologist, vol. 35, p. 366, 1905.

[68] Merriam, Richard, Igneous and metamorphic rocks of the southwestern part of the Ramona quadrangle, San Diego County, California: Geol. Soc. America Bull., vol. 57, pp. 242-243, 1946.

[69] Schaller, W. T., op. cit., pp. 274-277, 1925.

[70] Schaller, W. T., op. cit., pp. 274-275, 1925.
Schaller, W. T., personal communications, 1943-1948.

many high-quality porcelains and enamels, in which it is an effective opacifier.

Lepidolite containing 3 percent Li_2O has generally commanded a price of \$15 to \$27 per short ton (\$5 to \$9 per short-ton unit) at the mine, but during the period 1945-47 prices rose to as much as \$17 per ton-unit, or about \$50 per ton for 3-percent material. Prices have dropped since 1947, mostly because of imports from southwest Africa.

Most of the lepidolite shipped from the Pala district was obtained from the southern part of the Stewart pegmatite. Small quantities of the mineral were taken from the Pala Chief and Vanderburg-Katerina pegmatites also, and at times from the Tourmaline King, Tourmaline Queen, and numerous other dikes. The bulk of the output was processed as a source of lithium and lithium compounds. A little material was polished and carved, and some of the lepidolite with sprays of opaque pink tourmaline was highly prized as specimen material.

The largest concentrations of lepidolite occur as dense aggregates of small, white to deep-purple flakes and plates. In general those of finest grain and most bluish, blue-gray, or darkest-purple color contain the highest proportions of lithium. Some of the waxy, bluish aggregates contain more than 5.5 percent Li_2O, but the proportions of lithium oxide in most of the coarser pink- to lilac-colored material that was mined ranged from 2.5 percent to 4.5 percent.

The lepidolite of the Pala district is a common pocket constituent. The only known commercial concentrations are in the central parts of the dikes, especially in the footwall parts of massive quartz and of other quartz-rich units of very coarse-grained pegmatite. Even the purest concentrations grade outward into stockworks and ramifying veinlets of lepidolite in quartz or other pegmatite. Commonly associated minerals are quartz, albite, tourmaline, muscovite, and spodumene.

The concentrations of lepidolite that were mined were broken out, sorted underground or at the portal of the mine, and hauled in lump form by wagon or truck to such rail shipping points as Temecula and Fallbrook. In the largest ore bodies there was little difficulty in obtaining fairly pure material, or at least material contaminated only by quartz or small quantities of spodumene and feldspar. Although most of the Pala lepidolite was used as a source of lithium salts, some of it obtained during the last periods of operation was employed in glass making. In addition, both caesium and rubidium were extracted from several tons of concentrates that were refined in Germany before 1900 and in Los Angeles during the period 1935-1938.

Spodumene and Amblygonite

Spodumene and amblygonite are employed directly in the manufacture of certain glasses to neutralize shrinkage during cooling, and are also ingredients of some ceramic mixes. Most of the domestic consumption of these minerals, however, is founded upon their use as sources of lithium metal and lithium compounds. Salts of lithium are employed in pharmaceuticals, storage batteries, flares and fireworks, fluxes, and in curing meat, manufacturing textiles, refining metals, smelting iron ore, and in dehumidifying air in air-conditioning equipment. Lithium hydride has been employed as an effective transporter of hydrogen in self-inflating rafts, balloons, and other devices, and the metal is a minor constituent of some special-purpose alloys. Lithium also promises to become important as a raw material for certain types of nuclear reactions.

The average price quoted for spodumene during recent years has been about \$30 per short ton of clean cobbed or milled material, generally with a minimum Li_2O content of 5 or 6 percent. Prices for amblygonite, which contains more lithium, ordinarily have ranged from \$40 to \$50 per short ton. During World War II prices for spodumene concentrates rose to \$50 or more per ton, and then dropped considerably, even before the close of hostilities.

Spodumene occurs in the central parts of numerous dikes in the Pala district, and is most abundant in the Stewart, Pala Chief, and Vanderburg-Katerina. It is associated chiefly with very coarse-grained anhedral quartz, and the two minerals generally form cores or intermediate zones. Such units overlie most large concentrations of lepidolite, and in a few places occur sparingly beneath such concentrations. Most of the large spodumene crystals are slightly altered; in general, the pegmatites that contain the largest concentrations of lepidolite contain also the highest proportions of completely or nearly completely altered spodumene.

Coarse masses of amblygonite occur mainly in the outer parts of the quartz-spodumene zones, and also in overlying units rich in coarse quartz and giant crystals of perthite. Most of the pegmatites in which the amblygonite occurs are so thin that it is mined along with lepidolite and spodumene if at all. The amblygonite and spodumene commonly are associated with albite, muscovite, and lithium-iron-manganese phosphate minerals.

A little non-gem spodumene has been recovered from the Pala pegmatites by hand picking, but production from a given dike never has been sustained for appreciable periods of time. Much of the mineral has been so thoroughly altered that its lithium content is very low; and its characteristically thin, lathlike habit makes it difficult to recover the mineral efficiently by the usual hand-sorting methods. In most dikes spodumene is not readily obtained in large quantities as a by-product, mainly because it does not occur in the same rock units as the minerals ordinarily sought. The altered nature of the spodumene also makes practical difficulties in mining, as it results in badly broken and otherwise heavy ground that requires timbering in some places.

In only a few pegmatites has amblygonite been encountered in sufficiently large concentrations and near enough to masses of other desirable minerals to make mining economic. The outstanding examples are in the Stewart and Katerina mines.

Feldspars

Commercial feldspar is used chiefly as an ingredient of glasses, glazes, pottery, and other ceramic products. It is employed also in various ways as an abrasive, building material, and grinding agent. It is generally graded on the basis of its freedom from iron and its content of free silica. Small quantities of admixed quartz commonly are accepted for most uses of ground feldspar, but the tolerance for iron is very low in nearly all grades. Biotite, garnet, and other iron-bearing impurities impart an objectionable discoloration to most ceramic products in which the feldspar is used.

Pegmatite feldspar ordinarily is hand cobbed at the mine, and then is shipped to nearby plants for grinding and blending. During recent years feldspar from pegmatites and from finer-grained igneous rocks has been recovered by flotation methods, which have proved satisfactory.

Most mine-run feldspar is a mixture of microcline or orthoclase and sodic plagioclase. Commonly a little quartz also is present. Prices for such material at or near the mine range from $3.50 to $12.00 or more per long ton; a general 25-year average for all common grades is nearly $6.00. The distance of most western deposits from principal centers of demand makes it economic to produce and ship only the best grades of material. Some extremely pure potash feldspar, used chiefly as high-grade abrasive material, yields returns of $2000.00 or more per ton, but the quantity of such material marketed during a given year is ordinarily measured in pounds, rather than tons.

A little potash feldspar has been recovered as a byproduct during past operations in the Stewart mine, and in 1949 a small stock pile still lay in the Main cut. Not only the Stewart, but many of the larger and more bulbous dikes in the Pala district contain large masses of perthite, with so little biotite or other iron-bearing impurities that the proportion of quartz would be the principal consideration in any selective mining. Many cores and intermediate zones that are rich in massive quartz also contain several tons of individual crystals and crystal groups of top-quality perthite. Other high-quality material, and also some of inferior grade, occurs in the intermediate zones and cores of coarse, blocky perthite. Although graphic granite has been mined and marketed in some districts, this material, so abundant in the Pala area, is probably not salable, chiefly owing to the geographic location of the deposits.

In general, the parts of the Pala dikes that contain coarse feldspar of best quality occur above the horizon of the pockets, and below the hanging-wall units that are rich in graphic granite. Inasmuch as they do not occupy the same position as lithium- and gem-bearing parts of the dikes, these feldspar concentrations can be recovered only by additional mining, rather than as byproducts from the material removed during operations for the other minerals.

Some of the pocket pegmatite contains a clear variety of perthitic orthoclase and microcline that is known in the trade as "dental spar." It is used as an abrasive in dentistry, and ordinarily commands prices of $1.00 to $5.00 per pound. Coarse crystals of clear potash feldspar are particularly abundant in the Pala Chief, Tourmaline King, Tourmaline Queen, San Pedro, Katerina, Senpe, and El Molino pegmatites, and exceptionally large quantities of it are present in the main dump at the Senpe mine. Much of this feldspar is so deeply corroded and iron-stained, however, that it would require much careful cobbing and trimming before iron-free and quartz-free material of dental quality could be recovered.

Gem Minerals

Tourmaline

Much of the tourmaline in the pockets of the Pala pegmatites occurs in large crystals that contain clear, unfractured material admirably suited for gem uses. The mineral is graded on the basis of size, color, or color combinations, transparency, and freedom from bubbles, inclusions, cracks, and other imperfections. Material of red, pink, salmon, green, dark blue, black, and other colors has been cut into gem stones, but the pale- to deep-pink tourmaline undoubtedly represents the dominant commercial production, in terms of both bulk and value. Its color, which contrasts sharply with the much deeper red of Brazilian rubellite, is very attractive.

Most material of good quality has commanded prices of $2.00 to $35.00 per carat in the cut form, depending largely upon the color or colors involved. In general the recent prices have been slightly higher than heretofore. The period of greatest demand for tourmaline of gem quality was in the early part of the century, when the principal market was in China. The Chinese prized the pink and red varieties of the mineral very highly, and they carved and polished it into many different forms. With the collapse of the Chinese dynasty in 1912, however, most of the Oriental market was eliminated, and there resulted a drastic curtailment of mining for tourmaline in the United States.

The best grades of tourmaline are most popular for facet-cut gems. The stones are cut parallel to the length of the crystals in order to reduce waste of usable material. Thus, such elongate cuts as baguettes, triangles, kites, lozenges, trapezes, and the like, are commonly used for this mineral. This style of cutting is best also in terms of color of the finished stone, as the lightest tints can be obtained when the mineral is viewed normal to its elongation.

Inasmuch as the quality of color is generally considered of more importance than fire and brilliancy in tourmaline, the relatively flat types of table, baguette, and step, or trap, cuts are particularly popular. Some stones of exceptional size, 100 carats or more, have been obtained from Pala material. Like those from most other districts, however, such large stones are rarely unflawed. Some tourmaline is cut brilliant, and shows moderate sparkle and fire, especially where the table of the cut is parallel or nearly parallel to the base of the crystal.

There are many color variations within single crystals, especially in the green types. Some variations are gradual, others are sharply bounded. Pink and green, or pink, white, and green stones, are the most popular among the bicolor and multicolor gems, especially where the contacts between different colors are sharp (pl. 8-B).

The poorer types of material, generally marred by cracks, feathers, and tubular cavities, are cut in cabochon form, or are polished and carved into various types of ornaments. Especially suited to this kind of treatment are large fragments of partly flawed tourmaline broken from crystals of pale to deep-pink color. They were especially prized by the Chinese. An unusual type of tourmaline, found in only a small proportion of the crystals, is marked by groups of subparallel cylindrical cavities or threadlike inclusions, which give it a well-defined chatoyance. These stones yield good cat's eye cabochons of various colors.

Some deep-blue and bluish-black material that is relatively free from flaws was used during the recent wartime period as frequency-control plates in special electrical equipment. Only a small proportion of these crystals was found to be usable, as the tolerances for flaws, inclusions, and other irregularities are very strict. Tourmaline is also the basic element of certain types of pressure gages, in which its piezoelectric qualities are used. Some types of flawed material are acceptable for such equipment, and the specifications have been outlined in detail by Frondel [71]. Material that is too dark to yield attractive gems can be used, and a quantity of large, dark-colored crystals and crystal fragments that had accumulated in shops and storage sheds was quickly absorbed by the recent wartime demands for such devices.

Gem tourmaline is strictly a pocket mineral, and little but schorl occurs in the regular pegmatite zones. The gem crystals are most abundant in the Tourmaline King, Ed Fletcher, Tourmaline Queen, in parts of the Stewart and Pala Chief, and in several dikes on Hiriart Mountain. Ordinarily they are not at all common in dikes or parts of dikes with high concentrations of spodumene. The associated minerals include quartz, albite, orthoclase, microcline, muscovite, and lepidolite, and in most places the crystals of tourmaline are encased in white to pinkish clay.

Specimen material, including both individual crystals and crystal groups, has found a ready market. Many of the crystals contain material of more than one color, and are very attractive. Small, well-formed pencil-like crystals have been sold in all parts of the world. Aggregates of tourmaline crystals and other coarsely crystalline minerals, generally known as matrix specimens, are present in thousands of collections. These specimens ordinarily contain tourmaline with cleavelandite, quartz crystals, mica, microcline, and orthoclase.

Spodumene

The pink, green, yellow, and colorless gem varieties of spodumene constitute a small proportion of the total spodumene in the Pala pegmatites. The pink to pale-purple kunzite, sometimes termed "California's own gem," has been much sought after throughout the district since its discovery on Hiriart and Chief Mountains in 1902. It is valued mainly for its transparency and its exceptionally clear and beautiful colors. In addition it was very fashionable during the early part of the century because of its rarity and the fact that it was then the only exclusively American gem. During more recent years, however, kunzite has been obtained commercially from deposits in Madagascar and Brazil.

The kunzite occurs with the green hiddenite and the white to straw-yellow triphane varieties of spodumene. In many respects they yield gems almost as attractive as kunzite, but they never have found as ready a market or as much favor among collectors. The Pala hiddenite is a very pale green, and hence not as highly valued as the deeper-colored material from North Carolina, and the triphane does not have colors sufficiently deep or attractive to command the attention received by kunzite. The kunzite itself ranges from very pale rose-pink through lilac to pale purple. Some of it has a faint bluish cast, and yields cut stones of great beauty.

During the period 1903-14, when kunzite and other types of gem spodumene were very popular, rough crystals of good color and high quality commanded prices of $10.00 to more than $50.00 per ounce. The price for any given piece depended then, as now, upon the nature and depth of its color. Facet-cut stones were marketed at prices of $4.00 to $30.00 per carat, with a probable average cost of not more than $8.00 per carat. Prices gradually dropped during later years, until cut kunzite of top quality was sold for as little as $5.00 per carat in the middle 30's. More recently, however, the popularity of gem spodumene has again increased, and current prices for good rough material average about $15.00 per ounce. Facet-cut stones are sold for $2.00 to more than $40.00 per carat, and most flawless stones are priced at $15.00 or more per carat.

Gem spodumene ordinarily is facet cut, for maximum brilliance, and most stones are cut very deep, so that the strongest possible color is obtained. The mineral is markedly pleochroic, and the deepest colors are seen when the stones are viewed parallel to the long axis of the crystal. Thus the limiting factor for size of top-quality cut stones is the thickness of the bladelike or rodlike source crystals. For optimum color and brilliance, such stones are cut with their tables nearly but not exactly perpendicular to the long axes of the crystals. The mineral is not an easy one to prepare as a gem, because of its two directions of perfect cleavage and its consequent tendency to break near the edges during cutting. Very careful sawing of the original gem blanks, however, ordinarily eliminates much of the objectionable chipping and "napping off" during subsequent grinding and polishing. Gem spodumene is fairly soft, and when subjected to hard usage its edges gradually lose their sharpness and its facets become somewhat dimmed. The color of some stones fades upon prolonged exposure to sunlight. This is most serious with the green, lavender, and pale-purple to bluish varieties, but the colors of most lilac, pink, and yellow stones appear to be very nearly permanent. Exposure to a source of strong X-rays changes the color of spodumene to an intense light green, but the mineral reverts to its original color when exposed to sunlight.[72] The green color appears to last indefinitely if the mineral is kept in darkness. Gem spodumene is thermoluminescent and possibly triboluminescent. It is strongly phosphorescent when exposed to X-rays, ultraviolet rays, radioactive emanations, and high-tension electric currents.

The rough crystals of clear spodumene are blade-, lath-, or rod-shaped, and nearly all are deeply striated, grooved, and etch-pitted. Some are twinned, with the twin planes parallel to their flat faces. Multiple twinning, involving five or more planes in a single crystal, is known but is not common. In most cut stones the twinning does not appear to be objectionable, and few of the twin planes are visible upon even the most careful scrutiny. Most crystals are less than 2 inches long, but some are at least 15 inches long and weigh 24 to 27 ounces. The short, thick crystals, characteristic of several pegmatites on Hiriart Mountain, yield relatively large cut stones, some of which weigh more than 200 carats.

Many kunzite crystals are attached to quartz, and most of those that have not been removed from the clay matrix in which they are commonly enclosed are clearly unaltered remnants of larger crystals, which in turn are typical of the coarse, jackstrawlike aggregates of spodumene in massive quartz or other minerals. The gem material thus appears to represent spodumene that is indigenous to some of the inner pegmatite zones.

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[71] Frondel, Clifford, Tourmaline pressure gauges: Am. Mineralogist, vol. 33, pp. 1-17, 1948.

[72] Pough, F. H., and Rogers, T. H., Experiments in X-ray irradiation of gem stones: Am. Mineralogist, vol. 32, pp. 34-35, 1947.

COLOR-ZONED CRYSTALS OF GEM TOURMALINE
Pala and Mesa Grande districts. Natural size. Don M. George Jr. collection, California Institute of Technology.

A. KUNZITE CRYSTAL

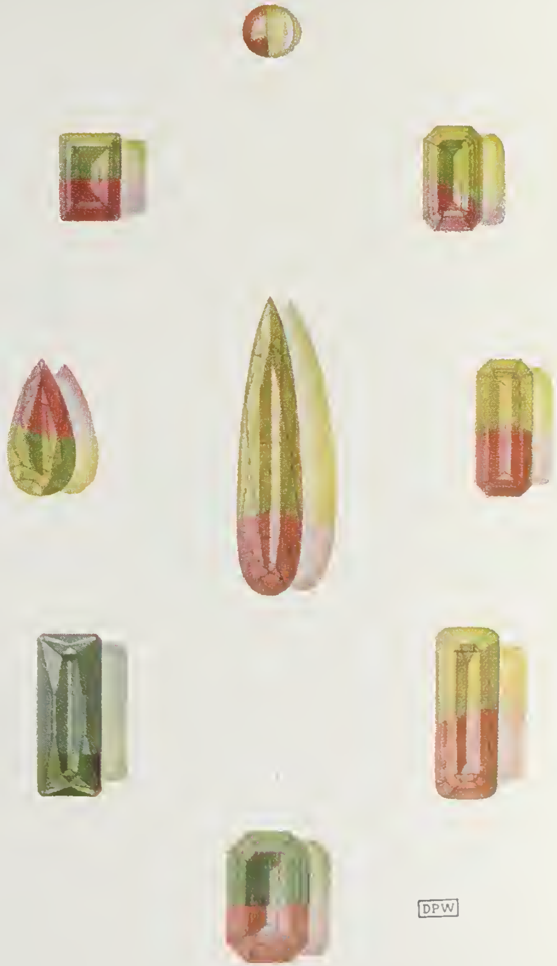
Approximately ¾ natural size. This specimen was in the original collection of Tiffany and Company, and is now part of the J. Pierpont Morgan collection in the American Museum of Natural History, New York.

B. CRYSTAL FRAGMENTS OF GEM SPODUMENE

Pala Chief mine. Two-thirds natural size. Pink to lilac—kunzite ; colorless to yellow—triphane ; green—hiddenite

A, TOURMALINE

Facet- and cabochon-cut stones. Approximately natural size. Note the cat's eye material, and the range of colors in the clear stones. F. G. McIntosh collection, California Institute of Technology.



B, TOURMALINE

Bi-colored cut stones. Approximately natural size. F. G. McIntosh collection, California Institute of Technology

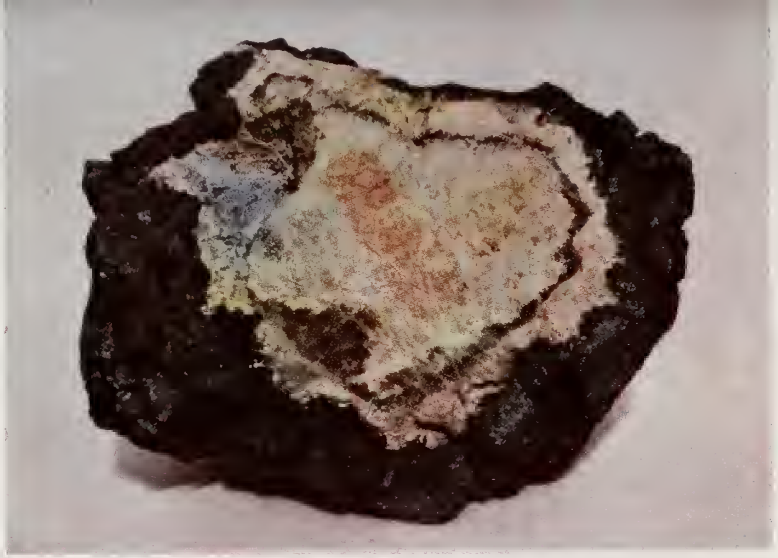
SPODUMENE
Facet-cut stones. Approximately ¾ natural size. F. G. McIntosh collection, California Institute of Technology.

A. FINE-GRAINED LEPIDOLITE

This pinkish to lilac lepidolite is typical of the best material obtained from the south ore body of the Stewart mine.

B. VERY FINE-GRAINED LEPIDOLITE

This lilac to bluish lepidolite with albite and abundant pink tourmaline is typical of the material obtained from the north ore body of the Stewart mine.



A. CRYSTAL OF LITHIOPHILITE

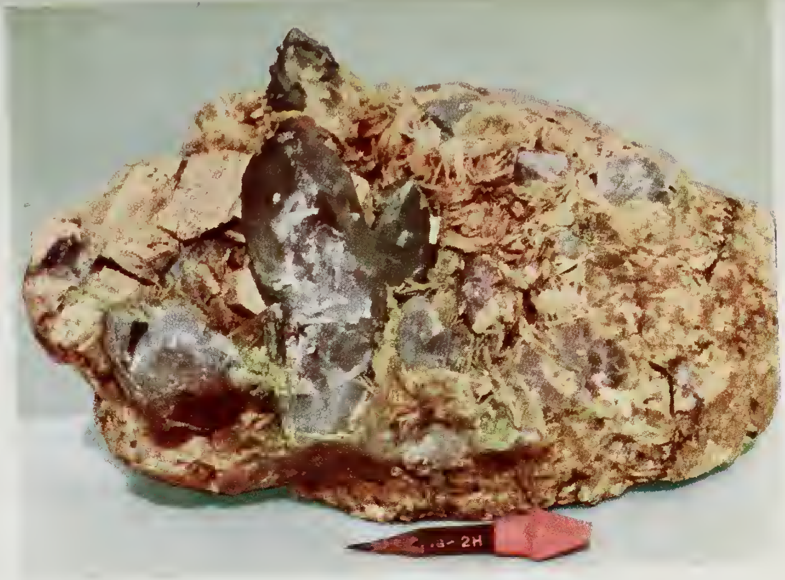
With alteration products, Stewart mine. Pale tan to flesh-colored lithiophilite is rimmed successively by flesh-colored hureaulite, deep reddish-brown sicklerite, buff to pale tan salmonsite, and salmonsite and other phosphate minerals stained with manganese oxides. In addition there are numerous crystalline aggregates of blue strengite, purplish purpurite, and canary-yellow stewartite. A thin veinlet of hureaulite (palaite) and stewartite cuts diagonally across the specimen, which is $5\frac{1}{2}$ inches long. Earl Calvert collection.

B. WALL ZONE AND LINE ROCK

Hiriart Mountain. Vanderburg-Katerina dike, gulch east of Katerina mine. Wall zone of graphic granite forms upper three-fifths of dike, here about 16 feet thick. Most of remainder is line rock, with fine-grained unlayered rock along footwall.

C. WALL ZONE AND VERY COARSE-GRAINED PEGMATITE

Very coarse-grained perthite-quartz-muscovite-albite-lepidolite pegmatite beneath wall zone rich in graphic granite. Katerina mine. Large mass of lepidolite about one foot beneath hammer head.

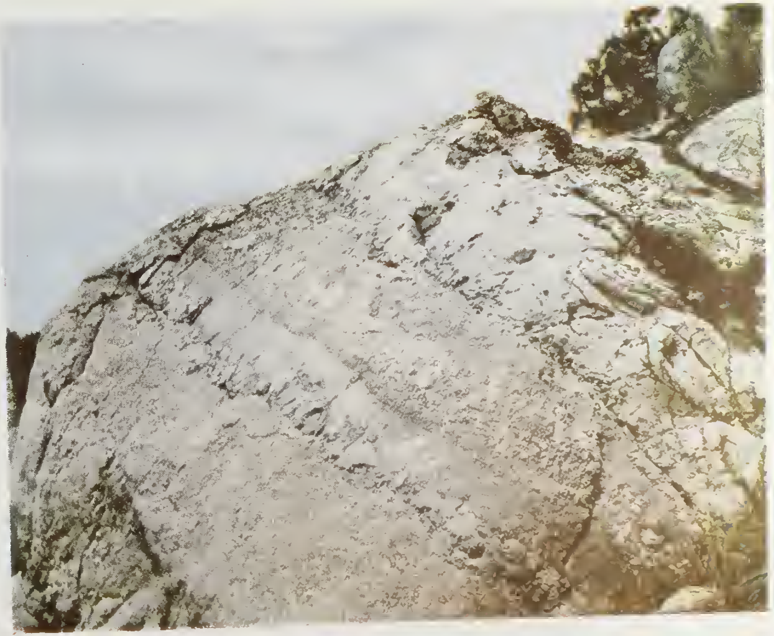


A. MATRIX SPECIMEN FROM A GEM-BEARING POCKET

Tourmaline Queen mine. Prismatic crystals of quartz, aggregates of cleavelandite tablets, and corroded crystals of orthoclase (upper left), with scattered small crystals of lepidolite and pink and green tourmaline.

B. LINE ROCK

Thinly and sharply layered line rock (above) adjacent to more homogeneous rock (below). South side of Hiriart Mountain.



C. COARSE-GRAINED GRAPHIC GRANITE

With fine-grained quartz-albite-perthite-muscovite-garnet pegmatite. Distribution of the two rock types is made clear by relatively rapid weathering of the fine-grained pegmatite. South side of Hiriart Mountain.

A. COLORED-ZONED TOURMALINE CRYSTALS

Showing parallel growth, Pala and Mesa Grande district. Both flat and pyramidal terminations shown. T. W. Warner collection, California Institute of Technology.

B. CRYSTAL OF MORGANITE

Of exceptional size and deep color, Himalaya mine, Mesa Grande district. T. W. Warner collection, California Institute of Technology.

C. SHORT, PRISMATIC CRYSTALS OF AQUAMARINE

San Pedro mine, Hiriart Mountain, Pala District. T. W. Warner collection, California Institute of Technology.

Beryl

Commercial beryl, which is used mainly in ceramics and as the principal source of beryllium metal and beryllium compounds, is so rare in the Pala pegmatites that its potential economic significance seems negligible. Gem beryl, on the other hand, is widespread, and has been recovered during the mining of numerous pegmatites. It is a minor constituent of some pockets in which it occurs as colorless to white goshenite, blue aquamarine, and pale-pink to peach-colored morganite.

The Pala beryl yields excellent cut stones. The morganite is particularly attractive and in general has a peach color that is in marked contrast to the pure pink of the Brazilian morganite. Square, baguette, table, and various types of step-cut stones are most popular. Generally they are cut very deep, in order to preserve as much color of the rough material as possible. Most good crystals yield stones of beautiful transparency, and many are of perfect quality. Others, however, are marred by tiny feathers or by very fine tubular cavities.

Quartz

Clear quartz is abundant in the pocket-bearing parts of most pegmatites, where it commonly forms large crystals. Although they are by no means as attractive as some of the other gem minerals, these crystals have yielded excellent cabochon and facet-cut stones. Colorless, smoky, milky, and rose-colored varieties have been used in this way. In addition, some crystals have been fashioned into polished spheres, and others have been carved. The pale-rose quartz in the cores of several dikes on Pala Mountain has been most popular for such use. A little of this material is sparsely rutilated.

Some of the clear crystals of quartz appear to be of "radio grade," as they meet certain tolerances with respect to the amount and distribution of twinning, inclusions, gas bubbles, and other flaws. Such material is in considerable demand at present, and commands prices of 50 cents to nearly $40 per pound, depending mainly upon the size and grade of individual pieces. The usable crystals are cut into oscillator plates of specified thickness, and these plates are employed for frequency control in radio, telephone, and special electrical equipment. Quartz crystals were obtained for this purpose from the Senpe pegmatite during World War II, and small quantities of acceptable material were recovered from them by the Universal Microphone Co. of Inglewood, California. Crystals in other mines also may be satisfactory, but the proportion of clear quartz reasonably free from twinning generally is too small to be of economic interest.

Other Minerals

Specimen minerals have constituted a significant proportion of the output from the mines of the Pala district, although few have been mined and sold commercially. Most of them have been obtained by mineral collectors, who have kept them in their own collections or have exchanged them for other minerals. Matrix specimens from pockets in the pegmatites have been most popular in this connection. They commonly include quartz, tourmaline, spodumene, orthoclase, cleavelandite, muscovite, lepidolite, and other, rarer minerals. In addition, specimen material from the Stewart mine has achieved wide circulation, chiefly in the form of sprays of opaque but attractive pink tourmaline crystals in massive aggregates of fine-grained lilac to blue-gray lepidolite.

Some exceptionally fine crystals of gem minerals are valued too highly by their owners to be cut up into stones, and others, although of great value as specimens, do not contain enough unflawed gem material to warrant further treatment. An excellent example is the beautifully crystallized peach-colored beryl obtained during World War II from the Senpe mine, chiefly as a by-product from operations for clear quartz. Few of these beryl crystals contain enough clear material to yield cut stones of very large size, although there are some noteworthy exceptions. Also of considerable value are some rare minerals, notably the crystals of lithium-bearing phosphates and their pseudomorphs in the Stewart pegmatite.

Many of the dumps in the district have been worked and reworked for inadvertently discarded fragments of valuable minerals, and a few of the dumps at the better known mines have been screened as many as eight different times. Even so, it is possible to collect very small fragments of tourmaline, kunzite, and other gem material on the surfaces of many dumps after periods of heavy rains. The main dump at the recently reopened Katerina mine was the object of critical scrutiny by hundreds of amateur collectors during the period 1947-49. In connection with guided trips through the mine, such persons have been permitted to collect material from the dump for a nominal fee.

In addition to the lithium and gem minerals, a little ornamental and monumental stone has been obtained from the pegmatites at irregular intervals. The graphic granite yields rather attractive patterns on polished surfaces, and has found favor for garden ornaments and, in rough form, for walls and other decorative structures. The line rock, especially garnet-rich types, has been used locally for fireplaces and monuments. A little quarrying of line rock boulders was done on the south face of Hiriart Mountain, not far from the Ashley Ranch house.

MINING

Prospecting and Mining Methods

Nearly all the deposits of lepidolite and gem minerals in the district were discovered through the tracing of float material to the source ledges. Loose fragments of lepidolite, tourmaline, and euhedral quartz, which were strewn on some slopes and in numerous gullies, were found to be particularly good indicators of pocket pegmatite higher on the hills. In a few places unusually rich concentrations of coarse, green muscovite flakes were traced to gem-bearing parts of nearby dikes. Rarely was it difficult to find or recognize the dikes themselves, even on the brushiest slopes. Their riblike or bouldery outcrops and their prevailingly light color distinguish them from the adjacent gabbroic rock.

The pocket-bearing parts of the dikes formed good outcrops in some places, and yielded concentrations of quartz-rich float in others, but the spodumene-bearing parts of the dikes were nowhere well exposed. Thus most discoveries of kunzite in place were essentially happy accidents involved in the devolopment of the pegmatites for other minerals.

Prospecting of the pegmatites themselves was done by means of small open cuts and shallow pits, and in a few places the full width of the Stewart dike was exposed by means of shallow trenches. Most of these prospect openings are now obscured by dense growths of brush and by slumped material and other rock debris. Some of the holes were enlarged to form irregular bench-like cuts, and others were extended underground. Where the edges of the dikes were well exposed, as on the east side of Chief Mountain, exploratory drifts were driven along the parts of the pegmatites considered most favorable for prospecting. Few of them are longer than 100 feet. Inclines were developed for the same purpose in other dikes, especially on the east slopes of Hiriart and Queen Mountains. On most ridges and westerly slopes, in contrast, the prospecting was largely confined to surface openings.

Whenever the results of preliminary excavations appeared to justify mining operations, open-cut work was carried on as long as the amount of barren overburden was not too great. The largest cuts of this type are those at the Stewart mine, and cuts and groups of cuts with maximum dimensions of 100 feet or more form parts of the Tourmaline King, Tourmaline Queen, Pala Chief, San Pedro, Senpe, Vanderburg, and El Molino mines.

Underground work was done mainly from drifts and inclines of gentle to moderate slope. The workings commonly were interconnected, especially in the largest mines. Some represent series of irregular sloping tunnels and rooms between drifts, like those of the Tourmaline King, Tourmaline Queen, and parts of the Stewart mine, whereas others are unsystematic networks of both inclined and level openings.

The few shafts sunk in the district were prospect holes or were used for mine ventilation. In four places with favorable topographic situation, efforts were made to tap lower parts of pegmatites by driving adits through the country rock, but none of these workings was continued far enough to accomplish its purpose.

Most parts of the pegmatite dikes are hard and unweathered, so that drilling and blasting were necessary in nearly all mining. The finer-grained, sugary parts of the dikes are particularly tough, and require considerable effort in their removal. Most of the work was done by hand methods, and maximum advantage was taken of joints and other natural features in breaking up the rock. Compressed-air drilling and otherwise mechanized mining were typical only of some operations in the Stewart, Tourmaline King, and in one or two other mines. The softer parts of the pegmatites, particularly the quartz-spodumene units and gem-bearing pockets, were easily handled with pick and shovel in many places, and little blasting was required except in masses of lepidolite and albite-rich rock. The most effective tools for excavating the gem-bearing parts of the pegmatites were the screwdriver, chisel, small pick, bar, and hammer. Indiscriminate blasting ruined quantities of gem and specimen material in some mines before more careful methods of hand-tool excavation were worked out.

Methods of handling the broken rock were generally very simple. The rock was loaded onto wheelbarrows, skips, or cars, and then lifted or trammed to the portal. Hand windlasses or mule-drawn whims were used for lifting at several mines. Much of the pegmatite in the Tourmaline King and Stewart mines was stoped and then carried by various combinations of tramming and chuting to the portals of lower-level adits. Most of the lepidolite and some of the gem material were sorted underground before tramming or between two stages of tramming, whereas most of the gem material was sorted from other constituents of the pocket pegmatite at the surface.

Little timbering was required in most mines, and today surprisingly few of the underground workings are caved or otherwise inaccessible. In most places, single stulls or sets of timber sufficed to support the walls or backs of workings. A notable exception to this is the Stewart mine, where square-set timbers were found necessary in some haulage ways and ore passes. This was due in part to badly broken ground, and in part to the mining away of all but a few thin pillars in the lepidolite-rich parts of the pegmatite. Much of this timbering has collapsed since the mine was abandoned in 1928, in part because no lagging was placed between it and the intricately fractured back of quartz-rich and spodumene-bearing varieties of pegmatite. The elements of all square sets were alined horizontally and vertically, rather than normal and parallel to the westward sloping pegmatite units, so that some timbering was collapsed by oblique stresses during large-scale caving.

Near some mine portals, at places where the pegmatite and wall rock are jointed, the weathered gabbroic country rock has caved. The backs of large rooms and other openings without adequate support have also caved, especially where the pegmatite is thoroughly fractured, as in parts of the Stewart and Katerina mines, or where it is cut by joints parallel to the hanging-wall contact, as in the Tourmaline King and Tourmaline Queen mines. In places, caving has progressively removed slabs of hanging-wall pegmatite, and part of the overlying gabbro.

Ground water is no problem in the mines, even in the deepest workings. Indeed, it was necessary to haul water into nearly all workings during periods of active mining.

Production

The recorded annual production of lepidolite and clear spodumene, tourmaline, and other gem minerals from the Pala district during the period 1900-47 is shown in table 5. The total reported output of lepidolite and amblygonite, 23,480 tons valued at $432,800, is undoubtedly slightly lower than the actual, or combined reported and unreported totals, but is probably substantially correct. The average value of this output was about $18.40 per ton, which probably is slightly lower than the national average for the same period. This fact might be in part attributable to the low grade of the material that was shipped, but in part also reflects production during periods when competition from other domestic deposits was keen. Most of the other deposits are more favorably situated with respect to centers of demand, and some of them have yielded material of higher lithium content.

The total recorded production of gem tourmaline, 2,980 pounds valued at $154,500, is incomplete in terms of both quantity and value. Production figures without data on value are available for two years, and value data without corresponding figures on quantity are listed for ten years. The total output comprises both rough gem material and some crystals of little but specimen value. Different mine owners and operators reported their production in terms of different kinds of material, so that figures for different properties—and even for the district as a whole during different years—have little comparative value. Probably more than two-thirds of the tourmaline production listed in table 5 represents rough gem material. The retail value of such material, in the form of its ultimate yield of cut gem stones, is approximately five times this figure.

The data on gem spodumene probably constitute a reasonably complete record of the formal production from the district. Most of the material was obtained from the Pala Chief mine, but some was produced from other parts of the district, particularly from mines on Hiriart Mountain. The total yield, 1,325 pounds of rough gem crystals and crystal fragments, was valued at $152,900 or at an average of approximately $115 per pound. The production figures mean little in terms of year-to-year comparisons, as much of the spodumene was sold several years or even a decade or more after it was mined. In most instances the value figures are based upon calculation, using the price schedules that were current at the time the material was obtained from the ground.

The information on production of other gem materials from the district, chiefly quartz and beryl, is far from complete, and the figures undoubtedly represent fairly small fractions of the actual formal production. Also, there is no means of determining the total quantity and value of specimen material taken from the district, although the figures must be large.

The total value of all gem material for which there is a record of production from the Pala district is at least $319,200. This amount is less than the value of the lepidolite taken from the Stewart pegmatite, and is considerably less than the $2,000,000 reported for all recorded pegmatite-gem production in southern California. All figures for the output of gem material represent only those totals for which there is a written record, and hence they must be minimum figures only. Only incomplete records of production are available for some of the mines, and no records at all are available for others, the operators of which either did not keep or did not release such data. Perhaps even more significant is the total of gem and specimen material removed from the pegmatites by amateur collectors, and—more important—by active high graders. These high graders include miners who withheld for personal use some of the output during regular mining operations, and individuals who carried on informal operations of their own during periods when the mines were shut down.

It is impossible to estimate accurately the total loss of gem material during the course of active mining in the district, but it must have been large. Also large has been the output of that picturesque group of energetic individuals who have mined the pegmatites from time to time without benefit of definite agreements with the owners. In many instances these men were remarkably shrewd in their interpretations of the pegmatite structure and the probable positions of desirable pocket material, and there is little question that in some mines they obtained a considerably larger yield of usable material per unit of pegmatite handled than did the actual owners of the mines during more regular operations.

In contrast to the high graders, the numerous amateur collectors who have been active in the district

Table 5. Recorded production of lepidolite and gem minerals from Pala district, San Diego County, California, 1900-1947.

Derived from records of the U. S. Geological Survey, U. S. Bureau of Mines, and the California State Division of Mines.

Year	Lepidolite		Tourmaline		Gem spodumene		Other gem minerals	
	Quantity (short tons)	Value (dollars)	Quantity (pounds average)	Value (dollars)	Quantity (pounds average)	Value (dollars)	Quantity (pounds average)	Value (dollars)
1900	[a], [b]1,200	[a]29,000	---	500	NR	NR	NR	NR
1901	1,400	37,500	425	---	NR	NR	NR	NR
1902	[c]820	31,900	[a], [d]600	[a]12,000	NR	NR	NR	NR
1903	30	100	[a], [d]500	[a]8,500	NR	NR	---	100
1904	[c]780	16,000	---	[a]16,000	[a]80	[a]10,000	NR	NR
1905	[a], [c]600	[a]9,500	---	[a]20,000	[a]50	[a]5,000	NR	NR
1906	[a]50	[a]700	30	---	80	14,000	---	1,500
1907	NR	NR	220	22,500	115	13,500	---	[a]2,000
1908	NR	NR	[a]260	17,000	80	14,500	---	[a]3,500
1909	NR	NR	[a]250	22,000	140	15,200	---	[a]1,800
1910	NR	NR	---	[a]5,000	120	32,000	---	[a]800
1911	[a]120	2,000	---	[a]4,500	20	5,500	---	[a]400
1912	NR	NR	---	[a]6,000	60	18,000	---	[a]300
1913	30	500	[a]100	[a]4,000	140	9,500	NR	NR
1914	NR	NR	---	[a]200	50	900	NR	NR
1915	90	1,400	40	[a]2,500	65	2,000	10	100
1916	[a]70	[a]1,000	---	[a]400	30	2,000	NR	NR
1917	880	8,800	NR	NR	30	1,800	100	100
1918	4,110	74,000	NR	NR	NR	NR	250	300
1919	800	14,400	NR	NR	NR	NR	NR	NR
1920	10,080	153,500	150	1,100	NR	NR	75	100
1921	700	10,600	100	900	NR	NR	10	---
1922	670	10,200	10	500	NR	NR	NR	NR
1923	NR	NR	NR	NR	70	2,300	15	---
1924	110	2,200	20	400	55	600	NR	NR
1925	NR	NR	110	3,500	NR	NR	NR	NR
1926	40	1,000	35	400	20	900	NR	NR
1927	500	12,500	10	500	30	1,500	NR	NR
1928	400	16,000	---	[a]100	10	900	---	200
1929	NR	NR	---	[a]200	10	900	---	[a]100
1930-1947	NR	NR	[a]120	[a]5,800	70	1,900	---	[a]600
Totals	23,480	432,800	[e]2,980	[e]154,500	1,325	152,900	[e]460	[e]11,800

NR—no recorded production; ---—no known production; [a]—approximate; [b]—includes nearly 800 tons produced during decade 1890-1899; [c]—includes some amblygonite; [d]—includes much material not of gem quality; [e]—totals incomplete.

probably have not accounted for such substantial quantities of gem crystals, except for many thousands of pounds of small or very low grade material. This is despite the great numbers of such persons, and the zeal with which they have scrutinized the deposits. Much of the material obtained in this way was waste rejected during mining and incorporated in backfill and in the numerous dumps. Although there is little basis for definite estimates, many persons familiar with the history of the district believe that the amount of gem material that has reached markets from the Pala pegmatites without having been recorded is nearly equal to the total of regular production indicated in table 5.

Future Possibilities

Nearly all prospecting and mining in the Pala district has stemmed from discoveries of commercially desirable minerals at the surface, and much detailed search for such surface outcrops has been carried on since 1892, the first year of systematic mining. The yearly number of new discoveries was decreasing as early as 1905, and by 1916 it had dropped to a small fraction of its former magnitude. As mining was extended farther and farther into the exposed concentrations of lepidolite and gem minerals, they were either worked out or the operations were stopped for other reasons prior to their complete removal. More recent activities have been confined mainly to recovering the remnants of these concentrations, and it is clear that any large-scale mining in future years must be based upon the discovery of additional concentrations, few of which are exposed at the present surface.

Near-surface pegmatite that contains desirable minerals can be sought out and exposed by rather simple means. Careful tracing of all pegmatites along their strike, with particularly close examination of their poorly exposed portions, might well yield helpful evidence of kunzite, lepidolite, or other pocket material. Attention should be devoted to those small, nearly flat areas that are strewn with angular fragments and large, subangular blocks of massive quartz. Several of them are present on Hiriart Mountain. The parts of such areas that are most likely underlain by pegmatite generally can be determined within narrow limits by projecting the trends of nearby dikes into them. The geologic map of the district (pl. 1) can be useful in this connection. The pegmatites themselves then can be exposed by means of shallow trenches and pits.

Several types of mineral occurrences are encouraging when encountered during exploration work, owing to their characteristic distribution within or immediately adjacent to pocket pegmatite. These types, listed in general order from the outer to the inner parts of the pegmatites, are as follows:

(1) Concentrations of coarse, prismatic schorl in the hanging-wall part of the pegmatite, especially where the mineral forms radiating, downward pointing clusters.

(2) Large masses of coarse-grained anhedral quartz, or of quartz with coarse, euhedral perthite, especially where such masses contain small, irregular cavities that are lined with quartz crystals.

(3) Tabular to ovoid concentrations of coarse book muscovite, especially where this material forms tightly intergrown aggregates of books ½ inch to 2 inches in diameter.

(4) Lepidolite, either as veinlets, stockworks, or as larger, more equidimensional masses.

(5) Fracture fillings and stockworks of cleavelandite, particularly in pegmatite rich in coarse, anhedral quartz.

(6) Irregular aggregates of very fine-grained blue tourmaline, which appear as powdery to sugary masses interstitial to masses of coarse quartz-, spodumene-, or albite-bearing pegmatite.

(7) Hypogene clay minerals, especially in large masses that contain angular fragments of quartz.

(8) Euhedral quartz crystals, especially where these crystals have an opaque, milky-white coating; these crystals lie within the pockets themselves.

Many of the pocket minerals occur as stringers and irregular but small masses in parts of the pegmatite adjacent to the main pocket horizon, and most large concentrations of these minerals are thus reflected by small-scale signs or outliers in zones nearer the walls. Such minerals, however, are by no means certain evidence for the existence of nearby gem-bearing pegmatite.

Nearly all the gem spodumene occurs in pegmatites that contain large or widespread masses of coarse-grained quartz-spodumene pegmatite, ordinarily in the inner parts of the dikes. Most of the gem material is in the outer parts of the quartz-spodumene zones, where it is enclosed by clay, quartz, and cleavelandite, in places accompanied by blue tourmaline and beryl. In general, clear spodumene does not occur in pegmatites or parts of pegmatites that contain fine-grained lepidolite in great abundance.

In most recent activities, further exploration of pegmatites in which is exposed some evidence of lithium minerals or gem concentrations has yielded poor to only moderately satisfactory returns. Such work appears to be headed in directions away from the desired concentrations, which have been either removed by erosion or mined out during earlier operations.

The size of a dike does not appear to govern its internal structure, so far as the existence of pocket-bearing pegmatite is concerned. On the other hand, the largest masses of such material occur in the largest dikes, and particularly in the interior parts of bulges. In observing and determining the thickness and bulgelike nature of the dikes, however, care should be taken to distinguish individual dikes from composite dikes and also from dikes that branch or join. The attitudes of known bulges in some dikes, and particularly their direction and degree of plunge, might well be used to predict the occurrence of other bulges or large-scale rolls at greater depths. Structural terraces or benches, perhaps containing good concentrations of tourmaline, spodumene, or lepidolite-bearing pegmatite, can be predicted by similar extrapolation, but only tentatively in most places.

Although relatively gently dipping parts of the dikes are commonly most favorable for the occurrence of desirable minerals, as in the Tourmaline King, Tourmaline Queen, Pala Chief, and several other dikes, there are notable exceptions. Segments of cores, and of other inner zones that contain many of the pocket concentrations, appear to be governed in their distribution by several different types of irregularities. Ordinarily they occur in the thickest parts of the dikes, but elsewhere they appear to be disposed in accordance with variations in the attitudes of dikes in which there is no perceptible thickening or thinning.

In some dikes there appears to be evidence of minor structural features which may serve as a basis for down-dip extrapolations. This is particularly true of several

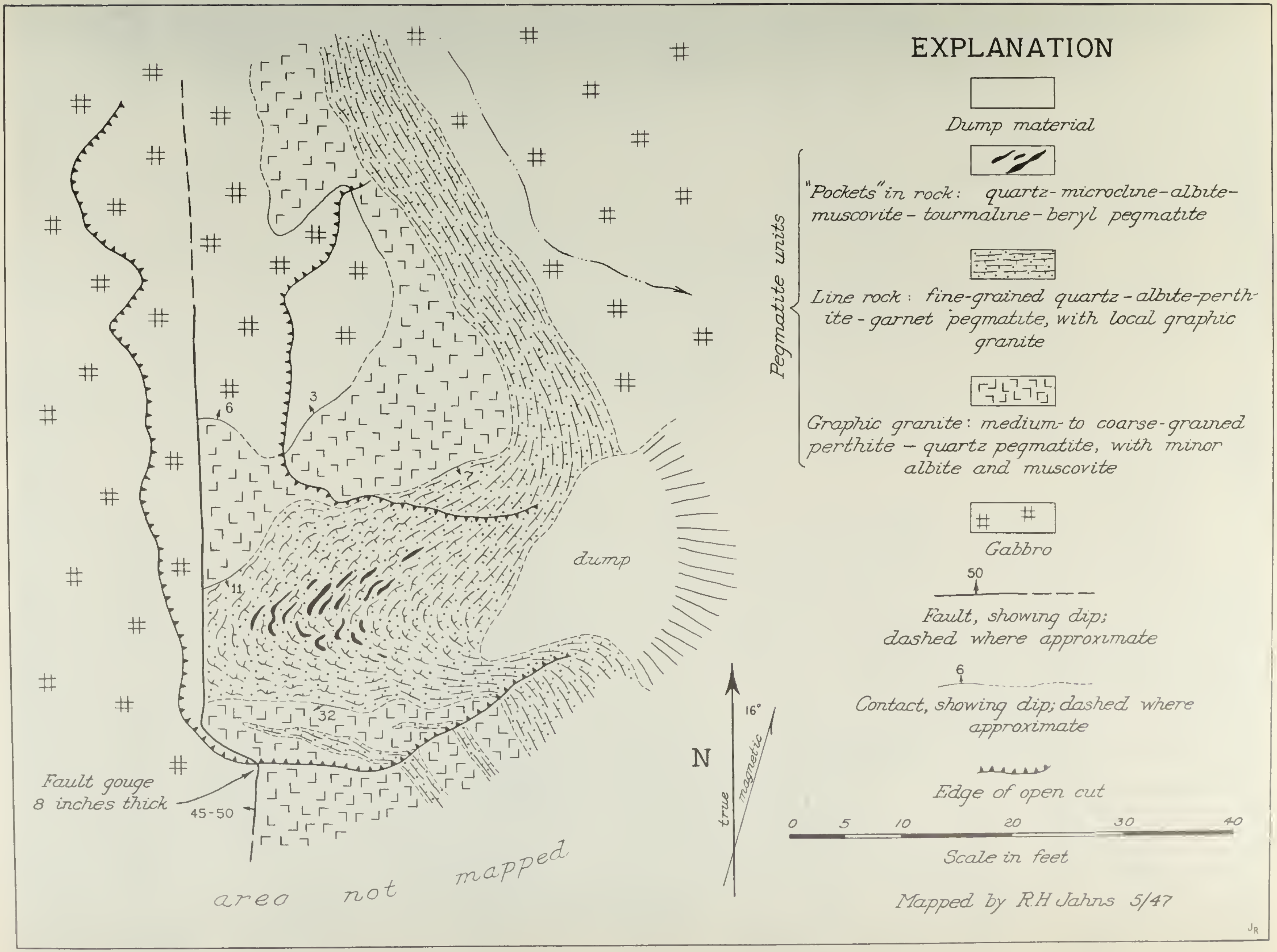


FIG. 23. Geologic sketch map of main cut, Naylor mine.

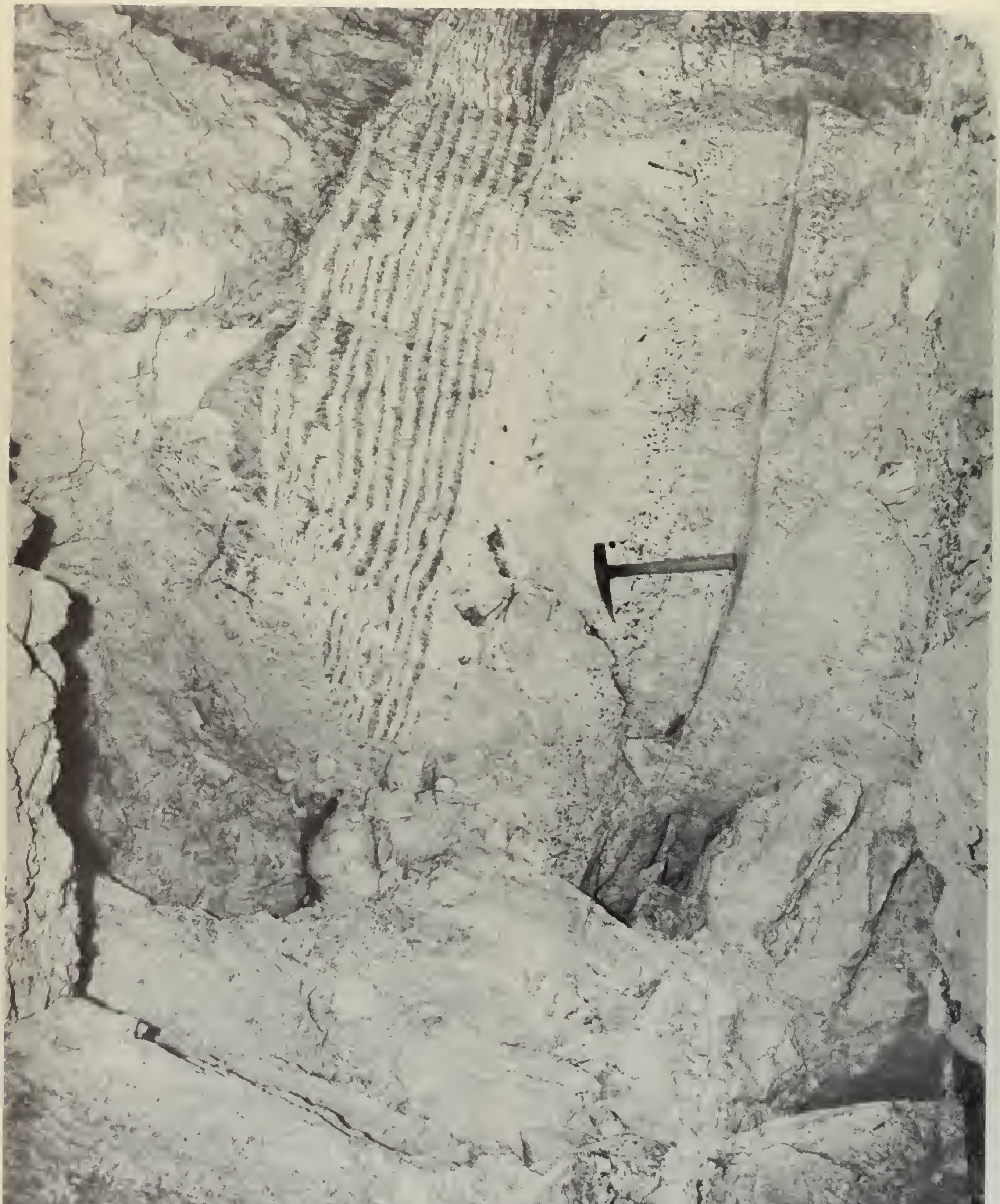


FIG. 24. Fracture-controlled replacement masses and small fracture-fillings of albite, White Cloud mine. Cleavelandite has replaced massive quartz (dark) along subparallel fractures to yield the layered zebra rock or stripe rock. This rock is in contact with graphic granite at left, and with massive quartz above. Below the layered rock are several types of finer-grained, albite-rich pegmatite, some with distinct layering of their own.

dikes on Chief Mountain, in which broad rolls and corrugations plunge parallel or nearly parallel to the dip. On the other hand, there are several pegmatites in which such structural features are not consistent. In the Tourmaline King dike, for example, a large and rich concentration of pocket minerals was encountered along a local flattening of the dike. Many thousands of dollars were spent in searching for additional concentrations of this sort, but neither such concentrations nor any flattenings of the pegmatite have been exposed.

In the broadest possible terms, the most promising pegmatites for prospecting and further exploration are those that contain units rich in coarse, anhedral quartz. Many of these units are accompanied at the surface by showings of quartz crystals and other pocket minerals, and some of them have not yet been explored. Even where such minerals are not present, most occurrences of the typical milky to transparent massive quartz probably merit at least small-scale testing. Few of the pegmatites or parts of the pegmatites in which there are very sharply defined, garnet-rich types of line rock are known to contain satisfactory concentrations of lepidolite or gem minerals. In most places where such line rock is exposed, it passes abruptly upward into barren, coarse-grained graphic granite.

The general outlook for revival of activity and renewal of production in the Pala district is only fair. Exposures in several mines suggest that additional reserves of gem-bearing ground are present, and numerous surface prospects appear to be favorable. If the geologic relations or the returns from exploratory work justify expenditures for subsurface exploration, some entirely new concentrations might well be discovered. Certain it is, however, that these new concentrations generally will be more difficult and expensive to find than those already known and worked.

DESCRIPTIONS OF SELECTED MINES

Tourmaline King (Wilke, Schuyler) Mine

The Tourmaline King mine is high on the northwest slope of Queen Mountain, due north of Pala (pl. 2). It can be reached by an old wagon road from the Stewart road to the south, or by trail from the abandoned site of Salmons City to the east. The surface workings lie at altitudes ranging from 1500 to 1700 feet, and comprise several small, irregular cuts for 450 feet along the trace of a pegmatite dike that trends northwest down the very steep slope. The dike has been mined extensively underground, and interconnected drifts, inclines, and irregular rooms constitute more than 1200 feet of tunnel. The mine was opened by F. B. Schuyler of San Diego in 1903, and during the early years of its operation yielded much gem tourmaline of exceptional quality. It was later purchased by R. M. Wilke of Palo Alto, who carried on a very thorough program of exploration but obtained only small returns.

The pegmatite dike ranges in thickness from a knife edge to about 16 feet, and its average thickness appears to be 8 feet or slightly less. It strikes north and dips 25° to nearly 40° W., and has an average dip of about 32°. In most of the mine workings the country rock is gabbro, but in the Canyon cut and other lower workings it is thinly foliated feldspathic quartzite and light-gray quartz-mica schist. As shown in plate 3, the dike appears to cut across a major contact between gabbro on the southeast and quartzite with small sill-like masses of gabbro on the northwest. This contact trends northeast in the immediate vicinity of the mine, but to the south it is more complex, and is marked by septa of gabbro that extend southward and westward into the quartzite. In most places the foliation and bedding in the metamorphic rocks trend east-northeast to northeast and dip steeply north-northwest to northwest.

The dike is marked by many rolls, most of which have amplitudes of 2 to 5 feet. One of them is well exposed at the extreme southeast end of the surface workings. Many of the rolls are represented merely by changes in dip, generally a flattening of 5° to 10°. The dike consists chiefly of coarse-grained graphic granite with subordinate albite and muscovite, although much of its footwall part is a fine-grained, sugary, albite-rich pegmatite with crudely developed planar structure. The pegmatite does not closely resemble the typical sharply layered line rock. In most places, the hanging-wall graphic granite can be traced downward into much coarser-grained graphic granite, and thence locally into thin, lenticular masses of quartz-euhedral perthite pegmatite. In a very few places, segments of a quartz core are exposed. The coarse-grained inner units form only a very small part of the pegmatite as a whole, probably less than 5 percent.

Much of the graphic granite contains abundant muscovite and biotite, chiefly as radial aggregates of rather coarse flakes and plates. Garnet is exceptionally abundant, and forms wine-red to salmon-colored euhedral crystals that locally constitute 15 percent of the rock. Many of these crystals are as much as 2 inches in diameter. Other garnet masses are subgraphically intergrown with quartz, and still others are surrounded by or intergrown with schorl. Here and there in the graphic granite, especially within a few feet of the hanging wall in the upper part of the mine workings, are concentrations of coarse lepidolite, pink tourmaline, and other typical pocket minerals. Many of them are in places formerly occupied by parts of graphic-granite crystals. Other masses of lepidolite, albite, and tourmaline fill fractures in the graphic granite.

The pocket-bearing part of the dike is very discontinuous and poorly defined. Most of the characteristic minerals are scattered as irregular bunches or knots through the coarse graphic granite and quartz- or perthite-rich pegmatite of the inner zones.

The only notable concentration of tourmaline and lepidolite was encountered and subsequently mined out in the workings immediately south of the Main cut. It occurred in a discoidal body of typical pocket pegmatite that was several tens of feet long, 1 foot to 6 feet thick, and at least 30 feet in maximum down-dip extent. It is said that this mass yielded the bulk of saleable tourmaline obtained from the deposit.

The interior parts of the dike are marked in many places by concentrations of coarse schorl, opaque pink tourmaline, coarse cleavelandite, and irregular masses of fine-grained lepidolite. The dumps contain abundant pocket material, and attractive specimens are still obtainable in several places. Many rosettes of coarse cleavelandite are coated with aggregates of lepidolite flakes and crystals, and extending from their surfaces are pencil-like crystals of rubellite. Most of the tourmaline appears to be slightly altered, and is opaque. Some aggregates of prismatic rubellite crystals occur in lepidolite, and resemble the material so abundant in the south part of the Stewart dike.

The deposit appears to have been thoroughly prospected, and indeed, there is much to suggest that the bulk of the pegmatite has been mined out. In many places, particularly in the inner parts of the upper underground workings, the keel of the dike evidently has been encountered. It fingers out into long, thin, subparallel septa that extend into the gabbroic country rock. Except for the one very large concentration of gem minerals encountered in the workings from the Main cut, the dike has yielded little commercial material, and it does not appear to offer great promise for future development.

Tourmaline Queen Mine

The workings of the Tourmaline Queen mine are high on the east slope of Queen Mountain, about 1500 feet east-southeast of the Tourmaline King mine (pl. 2). They are at an altitude of about 1600 feet and are best reached over a steep but well-conditioned trail that rises west-northwestward from the valley of Salmons Creek at the site of Salmons City. The mine is in the north part of a continuous pegmatite dike that is at least 3000 feet long.

The northern part of the pegmatite dike, where several masses of milky white quartz appeared at the outcrop, was first located in 1903 as a quartz claim by F. A. Salmons and associates of Pala. Exploratory work soon revealed lepidolite, pink, blue, and green tourmaline, and other typical pocket minerals, and the mine ultimately became the leading producer of gem tourmaline in the district. It was operated chiefly during the period 1904-14, and has been worked only intermittently since that time. It is now owned by the F. A. Salmons estate, and is administered by Monta J. Moore of Pala. A little development and assessment work during recent years has led to recovery of coarse crystals of quartz and deep-blue tourmaline.

The principal mine openings comprise two benchlike cuts along the trace of the pegmatite and extensive underground workings that were driven from the north, or upper cut. These workings consist of inclines, irregular drifts, and numerous low rooms, many of which are interconnected. In general they occupy an area 150 feet long, as measured along the strike of the pegmatite, and 80 to 100 feet wide. Not all are accessible as some of them have been backfilled and others are blocked by caved ground. In particular, the Main adit or incline is completely filled at its portal by large blocks that have slumped from the face of the open cut. At least one incline or irregular sloping room extends down the dip of the dike from the southern, or smaller cut, but it is no longer accessible. It appears to have been filled in part by caved material and in part by debris washed in during periods of heavy rain.

The Main, or upper open cut is about 130 feet long, 40 to 50 feet wide, and nearly 40 feet in maximum depth. The hanging-wall contact of the pegmatite dike is very well exposed in this opening, but the lower parts of the pegmatite are concealed in most places by a thick mantle of slumped material. The dike trends north and dips 10° to 30° W. in coarse-grained gabbro, which contains numerous septa and inclusions of platy, impure quartzite and quartz-mica schist in the mine area. Some of these are as much as 25 feet in outcrop breadth. In general they trend west to west-northwest and dip very steeply. A thin septum of partly digested quartz-mica-amphibole schist and small quartzite beds is exposed above the pegmatite in the wall of the Main cut, and a thicker mass of quartzite and schist appears near the portal of the North adit.

Both the country rock and the pegmatite dike are offset in several places along small faults, most of which trend east-northeast and dip very steeply. In general the south sides of these faults appear to have moved downward with respect to the north sides, but in only a few places does the amount of movement appear to exceed 20 feet. Shearing is well developed along the pegmatite-wallrock contacts in many places, and numerous closely spaced joints within the hanging-wall part of the dike also are parallel with these contacts.

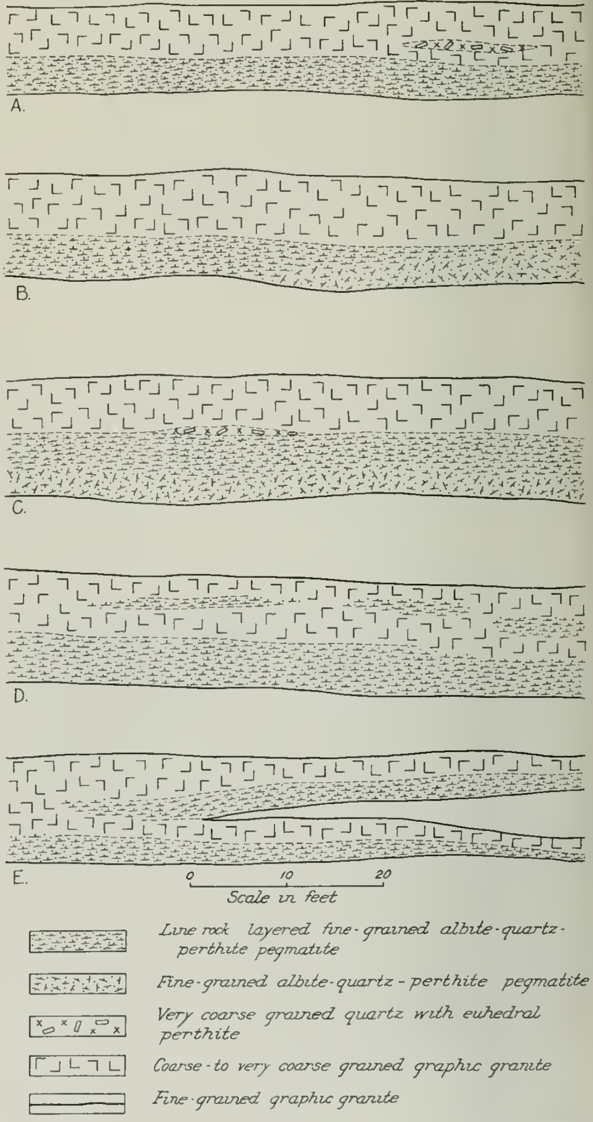


Fig. 25. Idealized section of pegmatite dikes in the Pala district, showing typical relations of line rock and associated fine-grained rocks.

Where exposed in the main surface and underground workings, the pegmatite is rather consistently layered.

It ranges in thickness from about 10 feet to as much as 18 feet, but in most places it is less than 15 feet. The dike is marked by rather gentle terracelike rolls, where the dip becomes less than 10° as traced for distances of 5 to 30 feet in a down-dip direction. These terraces are separated by much more steeply dipping segments. In addition, there are several much broader, more gentle rolls whose axes trend down the dip of the dike.

From hanging wall to footwall, the dike is layered as follows:

(1) A selvage of muscovite-perthite-quartz-albite pegmatite ranges in thickness from a knife edge to a maximum of 6 inches. This unit is best developed in the north half of the Main cut. In many places the muscovite occurs along fractures in fine-grained graphic granite, and also along the contact between the pegmatite and the gabbro.

(2) Graphic granite constitutes most of the dike. It is medium- to coarse-grained, coarsening downward from the hanging-wall selvage. In many places the quartz rods tend to be oriented normal to the pegmatite-gabbro contact, but there are many exceptions. This rock is transected by fractures and ½- to 5-inch fracture-controlled masses of muscovite and albite, with or without garnet and schorl. Most of the fractures are parallel to the hanging-wall contact of the dike. In some places in the graphic granite there are podlike to discoidal masses of closely intergrown quartz and muscovite, with some garnet and schorl; they commonly form a relatively fine-grained groundmass in a mosaic of graphic granite crystals.

(3) Scattered thin lenses of massive quartz with large euhedral crystals of perthite near the center of the dike are best exposed near the south end of the Main cut. Most of them are less than 10 feet long and 2 feet thick, but the original outcrop of the dike must have contained large segments of this unit.

(4) Typical pocket pegmatite is in and immediately beneath the segments of quartz-perthite core. This rock contains abundant quartz, with associated albite, schorl, alkali tourmaline, lepidolite, and other pocket minerals. Such material is exposed for a distance of at least 100 feet along the present trace of the dike, but at no place is it thicker than about three feet.

(5) Fine- to medium-grained albite-quartz-perthite pegmatite that contains plumose muscovite and local cleavelandite and schorl underlies the pocket-bearing rock. It may have been formed in part from coarse-grained graphic granite, remnants of which are scattered through it. Much of the muscovite forms thin, delicate sprays of plates 1 inch to 6 inches in maximum dimension. In a few places this rock contains as much as 10 percent schorl.

(6) Very crudely layered, sugary, fine- to medium-grained albite-quartz-perthite-muscovite pegmatite forms the footwall part of the dike. In some places it is in contact with massive quartz or other inner-zone pegmatite, but elsewhere it is separated from the quartz by graphic granite or by coarse-grained albite-rich pegmatite. Locally this rock contains sharply defined garnet-rich layers similar to those in the typical line rock farther east in the district, but in most places it is considerably coarser, and has little or no planar structure. The layered and unlayered rock types grade into one another, both along and across the strike of the layering. In general the more homogeneous forms of the rock are richer in fine-grained schorl than the layered types.

Much of the coarse, prismatic schorl in the lower part of the hanging-wall graphic-granite zone is clearly fracture controlled, as it extends outward from fractures or from planar positions that transect individual crystals and crystal aggregates of graphic granite. Much strip and blade biotite shows the same general relations with respect to the graphic granite and to the fine-grained footwall pegmatite (unit 6 above). Such mica is especially prominent where it lies normal to fractures, forming 1-inch to 6-inch stripes on the face of the Main cut.

Within the pocket-bearing parts of the dike, some of the coarser crystals of green muscovite are rimmed by pink to lilac lepidolite. Such muscovite also contains abundant inclusions of clear green tourmaline. Some crystals of schorl above the pocket horizon extend downward into this unit, and most of them grade along their lengths into green, and some into pink tourmaline.

The dike splits southward, and two dikes, separated by about 3 feet of gabbro, are poorly exposed in the lower, or south cut. The upper dike consists chiefly of coarse perthite, quartz, muscovite, schorl, and widespread garnet, and is 1½- to 4-feet thick. Although this dike is not well zoned, its central part contains irregular patches and stringers of lepidolite and other pocket minerals.

The lower dike, nearly 20 feet thick, is much more sharply zoned, but does not contain abundant pocket material. About 9 feet of graphic granite forms the hanging-wall half of the pegmatite, and passes abruptly downward into fine- to medium-grained albite-quartz-perthite-muscovite pegmatite, which is crudely layered in places. This rock contains much fine-grained flake muscovite. Both muscovite and biotite are also locally abundant in the overlying graphic granite, particularly near the hanging-wall contact. In the central part of this dike are local discoidal to lenticular masses of quartz-perthite pegmatite, and along the footwalls of these masses are the only stringers of lepidolite observed in the dike. Numerous thin, highly irregular cavities occur in this central discontinuous unit, particularly along or near contacts between the perthite and quartz.

The Tourmaline Queen mine has an impressive record of production, and according to available reports, gem material was obtained from most parts of the surface and underground workings. The total output from the deposit is not known, but a series of sales of gem tourmaline amounting to $48,000 was recorded for one year. Most of this material was marketed to eastern consumers, chiefly Tiffany and Company and the American Gem and Pearl Company of New York City. Assessment work during recent years has been done in a short, gently sloping incline that lies south of the caved entrance to the old Main adit or incline. Numerous pockets were encountered during the course of this work.

It seems likely that additional pocket-bearing ground is present in the pegmatite, not only in unmined areas that are surrounded by existing workings, but in parts of the dike down dip from the limits of the present underground workings. The gem-bearing part of the dike appears to extend almost directly down the dip, with possibly a slight component to the south. Most of the pockets appear to have been concentrated along the terracelike features in the pegmatite, and if additional flattenings of dip are encountered, the possibilities for further substantial returns of gem material appear to be fairly good. The pegmatite exposed in the south cut probably does not warrant much attention, as it is reported to become barren down the dip and to pinch out locally.

Gem Star (Loughbaugh) Mine

The Gem Star mine is in the thick Stewart dike, which crops out prominently on the east slope of Queen Mountain. It can be reached by trail from the Stewart mine to the south, from Salmons City to the north, and more directly from the road that adjoins Salmons Creek immediately to the east. The workings comprise several open cuts and appended inclines and drifts that are distributed along the pegmatite outcrop for a strike distance of about 500 feet. The mine was operated chiefly between 1905 and 1912 by a Mr. Loughbaugh, and during more recent years it has been worked intermittently by Francisco Moreno of Los Angeles. It is currently owned by Mr. Moreno. The past operations have yielded large quantities of crystal quartz and a little lepidolite and gem tourmaline.

The pegmatite is a thick composite mass that ranges in outcrop breadth from 100 feet to about 150 feet. In most places it clearly consists of three distinct dikes, which are juxtaposed without intervening masses of country rock. As traced from north to south in the mine area, however, the upper dike thins and is separated from the others by a thickening mass of gabbro. It pinches out entirely at the edge of the mine area. In most places the composite pegmatite mass trends north and dips westward at angles ranging from 20° to as much as 42°. Most of the mine workings are in the middle dike, which is 15 to 25 feet thick in most places.

FIG. 26. Composite pegmatite mass, east slope of Hiriart Mountain. The coarse-grained, lighter-colored pegmatite body is a sill (with some apophyses not shown in picture) in faintly layered, finer-grained albite-quartz-muscovite pegmatite. The coarser rock is rich in graphic granite, and contains local core segments of massive quartz and euhedral perthite (not in picture).

The principal opening in the north end of the mine area is a large, benchlike cut, known as the Whim cut, on the crest of an eastward sloping ridge. A 70-foot incline extends westward and leads to irregular drifts. North of these workings are two smaller cuts and appended short drifts, all of which are in pegmatite. South of the Main, or Whim workings is a series of shallow scratchings along a large clifflike exposure of pegmatite, and higher on the slope are two trenches excavated in the upper pegmatite. The openings from which most of the gem production was obtained are known as the Canyon workings, and lie at the south end of the mine area (pl. 34). They consist of two open cuts, from each of which branching tunnels extend westward and southwestward. The largest, or more southerly cut yields access to drifts and short inclines at two levels.

All the mine workings are in pegmatite that is rich in coarse graphic granite. This rock grades downward through a central coarse-grained schorl-rich unit into footwall pegmatite that is distinctly finer-grained and contains abundant albite, muscovite, and schorl. Most of the pocket material encountered in the Whim and nearby workings was beneath the coarse schorl-rich unit and within thin, discontinuous segments of massive quartz and of massive quartz with giant euhedral crystals of perthite. Little but quartz crystals was obtained. The discontinuous segments of quartz core and of perthite-bearing intermediate zone are chiefly in the upper dike, but some are present also in the middle dike.

Where exposed in the vicinity of the Canyon workings, the two lower dikes are 32 to 40 feet in combined thickness. Both are markedly asymmetric, with relatively thick hanging-wall units of coarse graphic granite and much thinner footwall units of fine- to medium-grained albite-quartz-perthite-plumose muscovite pegmatite that contains local concentrations of schorl. Both pegmatite and country rock are cut by a cross fault that is well exposed along the southern edge of the open cut.

The middle dike has a thin central unit of quartz-spodumene pegmatite, with accessory lepidolite, albite, and alkali tourmaline. The unit ranges in thickness from 1 inch or 2 inches to as much as 4 feet where exposed in the underground workings, and is characterized by an abundance of pale-pink to light-gray clay minerals. These and the other pocket minerals are scattered through the thin core of quartz-spodumene pegmatite. Above this unit, the graphic granite contains very coarse-grained schorl, which forms numerous sprays or radiating groups that point downward toward the pockets.

The tourmaline in the pockets is fairly hard, although much of it is sufficiently altered to be opaque. Many clear fragments of small crystals are present in the dumps, and some clear, gem-quality crystals as much as 4 inches in diameter and 15 inches long were recovered. The chief associates of the tourmaline are crystalline pink to lavender lepidolite, smoky quartz, apple-green albite, and very rare fragments of clear spodumene. All of these minerals are fringed or surrounded by pink clay.

The pocket-bearing pegmatite is fairly continuous throughout the Canyon workings, and is well exposed in the face of the incline that extends southwestward from the northwest end of the drift. Additional material of this sort probably remains to be mined, but the gem-bearing part of the dike is so thin and contains such a low proportion of unaltered, usable tourmaline that there might well be doubt as to the possible success of future mining operations. The pegmatite exposed in the workings farther north appears to be virtually barren of commercially desirable minerals.

Stewart Mine

The Stewart mine, once the most important domestic source of lepidolite, is in the bulbous south part of the Stewart pegmatite, and lies on both sides of a prominent ridge that forms the southeastern corner of Queen Mountain (pl. 2). The pegmatite itself is traceable for half a mile along the east slope of the mountain, on which it appears as a well-defined riblike feature. The mine workings can be reached over a road that extends eastward from the Pala-Temecula road, and also over several trails that ascend the slopes to the south and east.

Approximately 18 tons of lepidolite was taken from the deposit in 1892, the first year of mining, and the output was gradually increased during the following years. A substantial annual production was maintained from 1900 to 1907, when the price of lithium salts dropped as a result of the mining of amblygonite in the Black Hills of South Dakota. Most of the large-scale operations were conducted by the American Lithia and Chemical Company of New York. The mine was virtually idle until World War I. Maximum production was attained in 1920, after which mining activities dwindled, chiefly because of the development of the Harding lepidolite deposit in northern New Mexico. The National Industrial Chemical Corporation of New York worked the deposit for two or three years prior to its shutdown in 1928, and a little small-scale mining was done by several persons in the middle 30's. In addition to lepidolite, the output from the deposit includes some gem tourmaline and white, pink, and golden beryl. The mine is owned by Mrs. W. H. Crane of Oceanside.

FIG. 27. Thin prisms of schorl in medium-grained perthite-quartz-albite pegmatite, Gem Star mine, Queen Mountain.

The deposit was first worked along its outcrop by open-cut methods, with progressive development of the Main cut and the much smaller North and South cuts. The largest exposed mass of lepidolite-rich pegmatite was followed westward from the Main cut by means of a curving drift, from the inner end of which a short incline was extended downward at a moderate angle. A branch adit, driven southwestward from the same cut, was connected with the Old Main adit at a point not far from its portal. Irregular stopes, some of roomlike proportions, were developed from the inner part of the Main adit, and several drifts and low rooms were extended northwestward from points near the portal of the branch adit. The North adit was driven westward into the dike from a point below and east of the North cut, and an irregular exploratory adit was driven northwestward from a point near the Alvarado workings, in the south part of the mine area.

A large mass of amblygonite was encountered in the innermost part of the workings from the Old Main adit in 1903, and soon thereafter these workings were connected with the west slope of the hill by means of the Old West adit. Several irregular stopes and rooms were excavated during the period 1902-05, as shown in plate 6. Another adit was driven northeastward from a point fairly low on the west slope of the hill during World War I, and this opening ultimately provided efficient haulage for lepidolite recovered from the deposit during the most extensive operations in the wartime and postwar period. Extending eastward and northeastward from this adit and its principal branch drift is a complex series of irregular rooms and inclines, from which large quantities of high-grade lepidolite ore were recovered. During the middle 20's and for a short period during the middle 30's some lepidolite was removed from the North cut and from underground workings lower and to the southwest of this opening. These workings are connected with the surface by means of a steep incline and a vertical shaft.

Other workings in the mine area, chiefly of an exploratory nature, include open cuts in the hanging-wall part of the pegmatite dike low on the west slope of the hill, several small cuts along the pegmatite outcrop on the east side of the hill, a small open cut and 50-foot tunnel south-southeast of the Main adit, and a series of irregular shallow cuts farther east. The last are known as the Alvarado workings. A long adit was driven westward in the footwall gabbro from a point beneath the main lepidolite outcrop on the east slope of the hill, but not far enough to

FIG. 28. Schorl in gem-bearing central part of Tourmaline King dike. Irregular mass of crystalline lepidolite appears dark near lower right-hand corner. This schorl, also from Queen Mountain, is coarser than that shown in figure 27.

FIG. 29. Fragments of gem-quality kunzite in altered crystals of spodumene, Katerina mine, Hiriart Mountain.

penetrate the pegmatite dike. This work was done about 1900. It is reported that several winzes and inclines were sunk to points beneath the level of the Main adit during the middle 30's, mainly in an effort to find extensions of the known lepidolite shoots or additional shoots. One of these lower-level workings has been broken through to the surface about 50 feet south of the Main entry.

Nearly all of the underground workings are in hazardous condition, owing in part to caving from extensive unsupported backs of rooms, and in part to more local collapse of badly broken rock from the back, in a few places all the way to the surface. Although the high walls of the Main cut and part of the South cut were blasted down in the early 20's to eliminate use of the old adits, access to the underground workings was still possible through two small openings near the face of the South cut until the fall of 1948. The Main entry, which was timbered for its entire length, is partly collapsed and no longer accessible, but most of the workings with which it was connected can now be reached through the Old West adit. Many of the oldest workings, dating to the period 1900-05, have been backfilled or have been choked with slumped material. Some of the early stopes north of the large amblygonite stope near the West adit have completely collapsed, with formation of a large, quarrylike surface depression that is about 70 feet long and 25 to 35 feet wide. Nearly all of the workings connected with the North cut and the vertical shaft immediately south of this cut also are inaccessible or hazardous.

Two principal bodies of lepidolite were mined in the surface and underground workings. One of them, which extended westward from the Main cut, was about 200 feet long and 20 to 110 feet wide. Its thickness ranged from a knife edge to at least 20 feet, and was about 10 feet through much of the mined portions. This lepidolite is gray and bluish-gray to deep-purple in color, and most of it contains albite and abundant prismatic crystals of rubellite. In contrast to this material is the lepidolite typical of the other main ore body, which lies about 50 feet to the south. Most of this lepidolite rock is nearly pure, and only locally does it contain much albite and tourmaline. It is also characteristically coarser-grained and more reddish to pinkish in color than the material in the north ore body. The south ore body, which was poorly exposed in the South cut and was really discovered during the course of later, underground operations, was approximately 200 feet long, 30 to 180 feet wide, and locally as much as 18 feet thick. It was mined largely during the 20's.

In some places the lepidolite bodies are sharply defined from the adjacent rock, and particularly from a large mass of quartz-rich pegmatite that lies between them. In many other places, notably at the north bulge of the north ore body, the lepidolite pegmatite grades into quartz-albite pegmatite with abundant stringers, lenses, and irregular stockworks of lepidolite. Much material of this sort is exposed in the walls of the North cut and the appended underground workings. Additional masses of lepidolite pegmatite, some of them satellitic to the two main masses, are in several other parts of the mine area, but most of them are relatively small.

The pegmatite body, which is at least 80 feet thick in much of the mine area, forms a steep-faced outcrop on the east side of the ridge, and appears as a very gentle to moderate dip slope of hanging-wall graphic granite over much of the west side of the hill. The contact between pegmatite and overlying gabbro passes beneath the surface in the bottom of a small canyon immediately west of the mine area. Much of the longitudinal section of the dike on the east face of the hill is obscured by dump material and other loose debris, so that the internal structure of the pegmatite is best observed underground.

As indicated in the cross-section, the pegmatite comprises many zones arranged in layers around a discontinuous quartz-spodumene zone in its central parts. The spodumene-bearing pegmatite forms lenslike masses as much as 150 feet long and 10 to 15 feet in maximum thickness. They are poorly exposed at the surface, but appear in the walls and backs of many of the underground openings. Relatively thin lenses of massive quartz overlie the quartz-spodumene core segments. This discontinuous inner intermediate zone thickens enormously beyond the edges of the core segments along the strike of the dike, and is at least 30 feet thick where exposed between the Main cut and North cut at the surface. Much more continuous is a middle intermediate zone of massive quartz with large subhedral to euhedral crystals of perthite, which appears above the massive quartz unit. In a few places this zone consists almost wholly of perthite, with only local interstitial quartz, but elsewhere the quartz is dominant or the two minerals are in nearly equal proportions. Lithium-phosphate minerals are locally abundant in this unit.

Overlying the middle intermediate zone is a 10- to 15-foot outer intermediate zone composed of coarse, blocky perthite, with some quartz, muscovite, and albite. This zone in turn is overlain in most places by the typical coarse-grained graphic granite (with subordinate albite and muscovite) of the thick hanging-wall zone. Both the graphic granite and other perthite-rich units contain much coarse, prismatic schorl, especially at distances of 15 feet to 25 feet beneath the hanging-wall contact of the dike. Thin but continuous fracture-controlled units of muscovite, albite, and green tourmaline are locally abundant.

Beneath the quartz-spodumene pegmatite of the core in some places is the inner intermediate zone of massive quartz, and elsewhere are exposed the quartz-perthite pegmatite or the outer intermediate zone of coarse, blocky perthite. Much of the footwall part of the dike, however, consists of coarse-grained albite-quartz-muscovite pegmatite and sugary, fine- to medium-grained albite-quartz-schorl-muscovite pegmatite. These rocks are not notably marked by any planar structure.

Most of the lepidolite-rich pegmatite is in the footwall parts of the quartz-spodumene core, and may have been formed largely at the expense of this unit, remnants of which occur above and between the lepidolite lenses. Flanking the lenses themselves—and grading into them—are many masses of pegmatite that contain stringers and irregular networks of lepidolite.

The relations among the zones in the hanging-wall part of the pegmatite are somewhat complicated in places by at least one other, much thinner, juxtaposed dike. This dike also is zoned, but its core appears to be quartz-perthite pegmatite analogous to the middle intermediate zone of the main dike. The two dikes split as traced to the south, although in most areas the upper one has been removed by erosion. The main dike itself splits in the vicinity of the Alvarado workings. One prong tapers out abruptly, but the other extends for some distance southeastward down the ridge beyond the workings.

No pegmatite is exposed at the surface south of the mine area, but the results of some diamond drilling done in 1903 suggest that pegmatite is present at depth. Too little is known of the relations in the few underground workings beneath the level of the Main adit to permit an estimate of the shape of the dike in a down-dip direction. Several reports concerning the old workings indicate that a few septa of gabbro were encountered during the early stages of mining. Perhaps some of them represent screens between individual pegmatite dikes, particularly where they were near the hanging-wall parts of the main composite mass.

The large bodies of lepidolite-rich pegmatite are along or near a marked benchlike roll in the dike. In most parts of the mine area, this terrace lay between the relatively steeply dipping part of the pegmatite at the outcrop and another relatively steeply dipping segment in the lowermost part of the mine. Most of the lepidolite-rich masses taper out, or become markedly discontinuous as traced down their dips into this more steeply dipping part of the dike. Other large lenses of lepidolite-rich pegmatite may well be present in the dike, either north of the extensively stoped block of ground, or farther west and down the dip of the dike. The chances for such lenses in a down-dip direction probably would be enhanced materially if the steeply dipping segment of the dike in the vicinity of the lowermost mine workings should flatten. This possibility might well be tested by means of diamond-drill holes collared at points west of the small canyon that bounds the dip slope of pegmatite.

Exploratory work directed northwestward from the North cut failed to reveal additional masses of lepidolite, but such openings were not extended for great distances. The possibility that substantial quantities of lepidolite are north of the present underground workings also might be tested by means of diamond-drill holes. Although the two principal ore-bearing lenses are worked out, it is possible that there are other rich lenses of comparable size.

Mission Mine

The Mission mine, low on the south slope of Queen Mountain, is in a pegmatite dike that is crossed by the road to the Stewart mine (pl. 2). Both the mine workings and the dike are clearly visible from Pala, about a mile to the south-southwest. The deposit was worked between 1905 and 1925, but operations were intermittent and production never was large. The principal output was quartz crystals and some lepidolite, with a little tourmaline of gem quality.

The main mine workings are an open cut 20 by 35 feet in plan and an irregular 45-foot drift that extends northward from this cut. The drift is connected underground with another, slightly lower drift that was once reached from a cut immediately south of the road. This second drift is caved at the portal, but its outer part is accessible by means of a break-through immediately north of the road. Another open-cut lies along the trace of the pegmatite higher and to the northeast, and a fourth cut bounds the mine area on the southwest. An 85-foot tunnel, driven through gabbro in an unsuccessful effort to tap lower-level parts of the pegmatite dike, extends northward from a small cut in the southeastern part of the mine area.

The dike is 2 to 11 feet thick, and has an average thickness of less than 6 feet. It trends north and dips 25° to 35° W., so that its trace is southwesterly down the steep hill slope. The pegmatite-wallrock contacts are sharp, but in some places are complicated by many irregularities. A septum of gabbro 3 inches to about 2 feet thick divides the dike into two parts where it is exposed in the main drifts, and similar but even smaller irregularities in the contacts are exposed elsewhere in the underground workings. In the face of the Main cut the hanging-wall gabbro is transected by several steeply dipping apophyses of pegmatite. They appear to follow well-defined fractures. Both the pegmatite and the country rock are cut by several faults of small displacement. The most prominent break is exposed in the heading of the main drift, where the dike appears to be cut off by a slip plane. Cross joints, some of them slickensided, are abundant in parts of the pegmatite, and are responsible for heavy ground in several of the workings.

The internal structure of the dike is simple, and individual units are traceable for distances of at least 100 feet. The upper one-third to one-half of the dike is composed of typical coarse-grained graphic granite, and most of the lower part consists of very well-developed garnet-rich line rock. This unit resembles the line rock so common on Hiriart Mountain, in that it contains abundant garnet in sharply defined layers. In most places, however, it is slightly coarser-grained and its garnet-rich layers are slightly farther apart.

The central part of the dike in the vicinity of the mine workings consists of medium- to coarse-grained albite-quartz-perthite-muscovite pegmatite, which is locally very rich in coarse-grained quartz. The albite and muscovite are later than the other constituents, and locally are plainly concentrated along fractures. In the best-exposed parts of the dike, this central unit appears to be a partly ablitized composite, which consists of graphic granite in its upper part and discontinuous segments of a quartz-perthite core beneath. Remnants of perthite and graphic-granite aggregates are common. In most places the dominant constituents of the unit are coarse-grained albite with some schorl, muscovite, and other late-stage minerals. Only a few concentrations of typical pocket minerals are present, however, and all of them are in the main underground workings. Lepidolite occurs as lenticular to stringerlike masses ½ inch to 24 inches in maximum dimension.

No well-defined gem-bearing unit was encountered during mining of this deposit, and the total production of lepidolite and gem minerals has been small. The mine does not seem to offer great promise for future recovery of these minerals.

Pala Chief Mine

The Pala Chief mine, not far from Chief Mountain summit, is about 2 miles northeast of Pala (pl. 2). It can be reached from that town over an ungraded road and approximately half a mile of trail. The principal surface workings, several interconnected benchlike open cuts, form a distinct scar along the southwest face of a nearly flat-topped ridge. They are clearly visible from most areas to the south and southwest.

The mine was opened in 1903, and was operated most intensively during the following 15 years. Since that time, however, little but assessment work has been done. The pegmatite has yielded gem tourmaline, quartz, beryl, and lepidolite, but undoubtedly it is best known as the world's foremost source of gem spodumene. Most of the material produced was kunzite and triphane, but some green and some colorless material also were included in the output. The property was first located by Frank A. Salmons and associates of Pala, and is now owned by the Salmons Estate, of which Monta J. Moore of Pala is administrator.

The Main open cut, or series of cuts, is 280 feet long and 20 to about 65 feet wide. In places the excavation is 25 feet deep at the face, but in most of the mine area this dimension is not more than 15 feet. The series of cuts faces southwest, and is rimmed by a group of extensive dumps. Several irregular, interconnected underground workings extend northeastward from the central and southeastern parts of the cuts. Most of them are drifts or inclines with very gentle slopes, and many irregular rat-hole excavations have been developed from their walls. Other openings in the area, chiefly of an exploratory nature, include shallow cuts and trenches along the strike of the dike to the northwest and southeast, and also a cut and short tunnel in the footwall part of the deposit.

The pegmatite dike is only one part of a complex series of branching and joining dikes that in plan appears somewhat like a braided stream (pl. 2). Some of this branching is true splitting of a single pegmatite or a pair of juxtaposed pegmatites into two dikes separated by country rock. In other places this branching is only apparent, and instead is due to pronounced warps or rolls in the hanging-wall or footwall contacts of a single dike, with preservation of elongate masses of hanging-wall gabbro along some troughs and appearance of footwall gabbro through erosion-breached crests. Most of these rolls trend west, plunging directly down the dip of the dikes.

The main pegmatite mass is a dike 16 feet to at least 33 feet thick. It can be traced southward from the mine area for a distance of nearly 2000 feet, and extends westward for approximately 1200 feet to the valley of Salmons Creek, where it is buried beneath alluvium. Within this distance, the dike joins and diverges from numerous other dikes. It trends north-northwest to northwest and dips 5° to 55° southwest.

Coarse-grained graphic granite and subordinate albite and muscovite occur in the upper part of the dike as a unit 6 feet to at least 15 feet thick. The lower part of the dike, of equal or slightly lesser thickness, consists of fine-grained quartz-albite-perthite-garnet pegmatite with very poorly to very well-developed layering. In many parts of the mine area this line rock grades along the

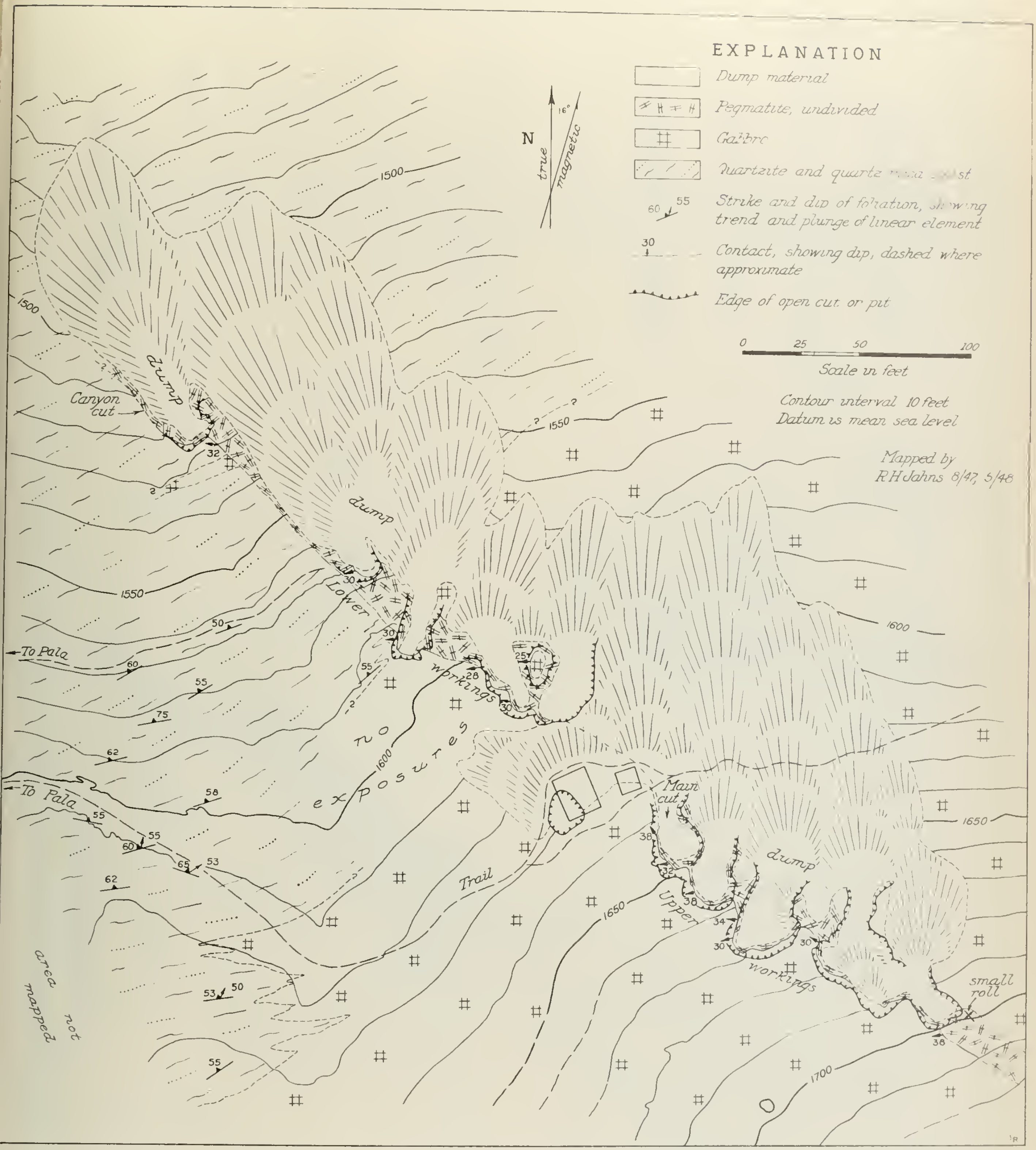


FIG. 30. Geologic map of surface workings, Tourmaline King mine.

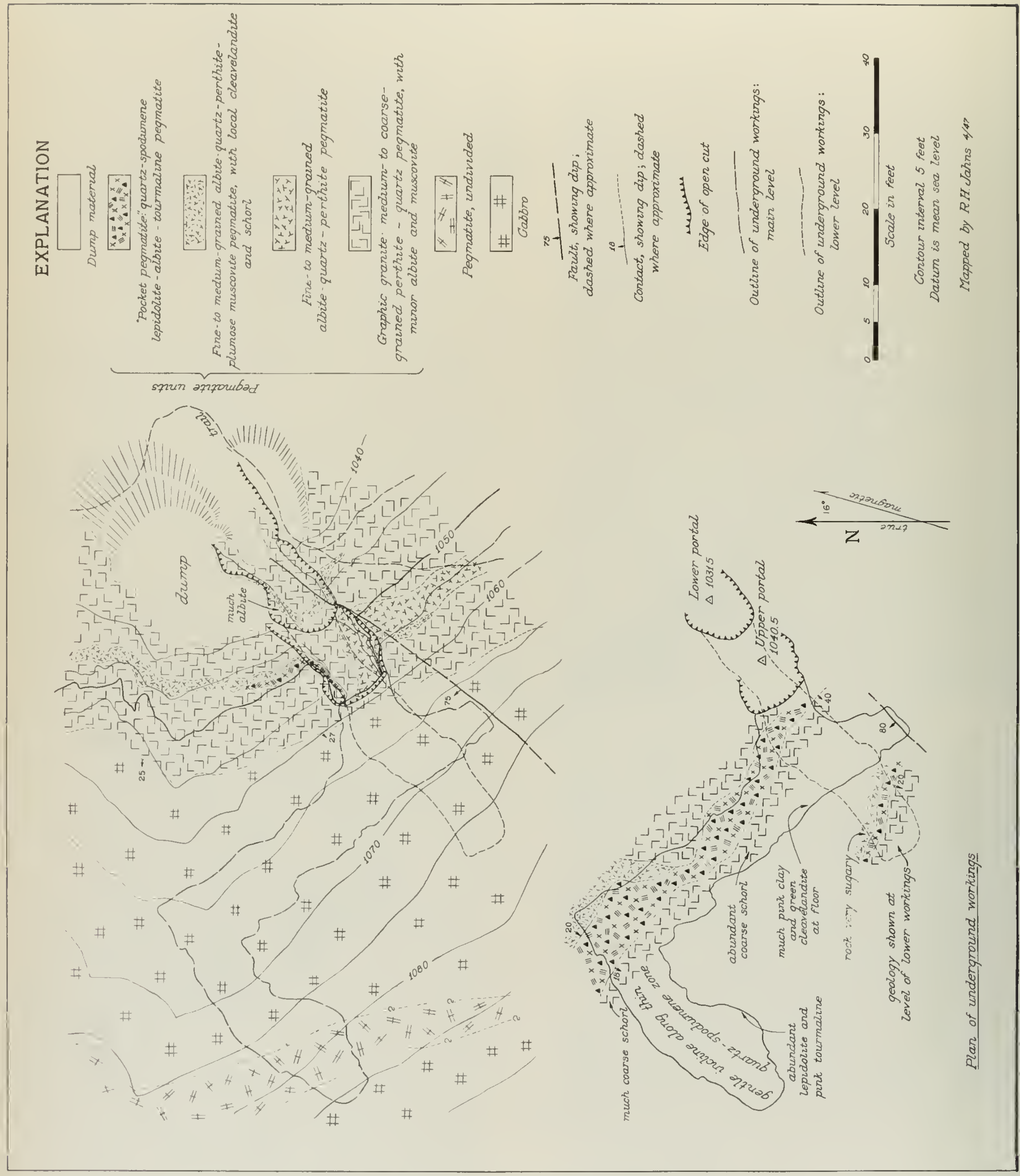


Fig. 31. Geologic map and plan of Canyon Workings, Gem Star mine.

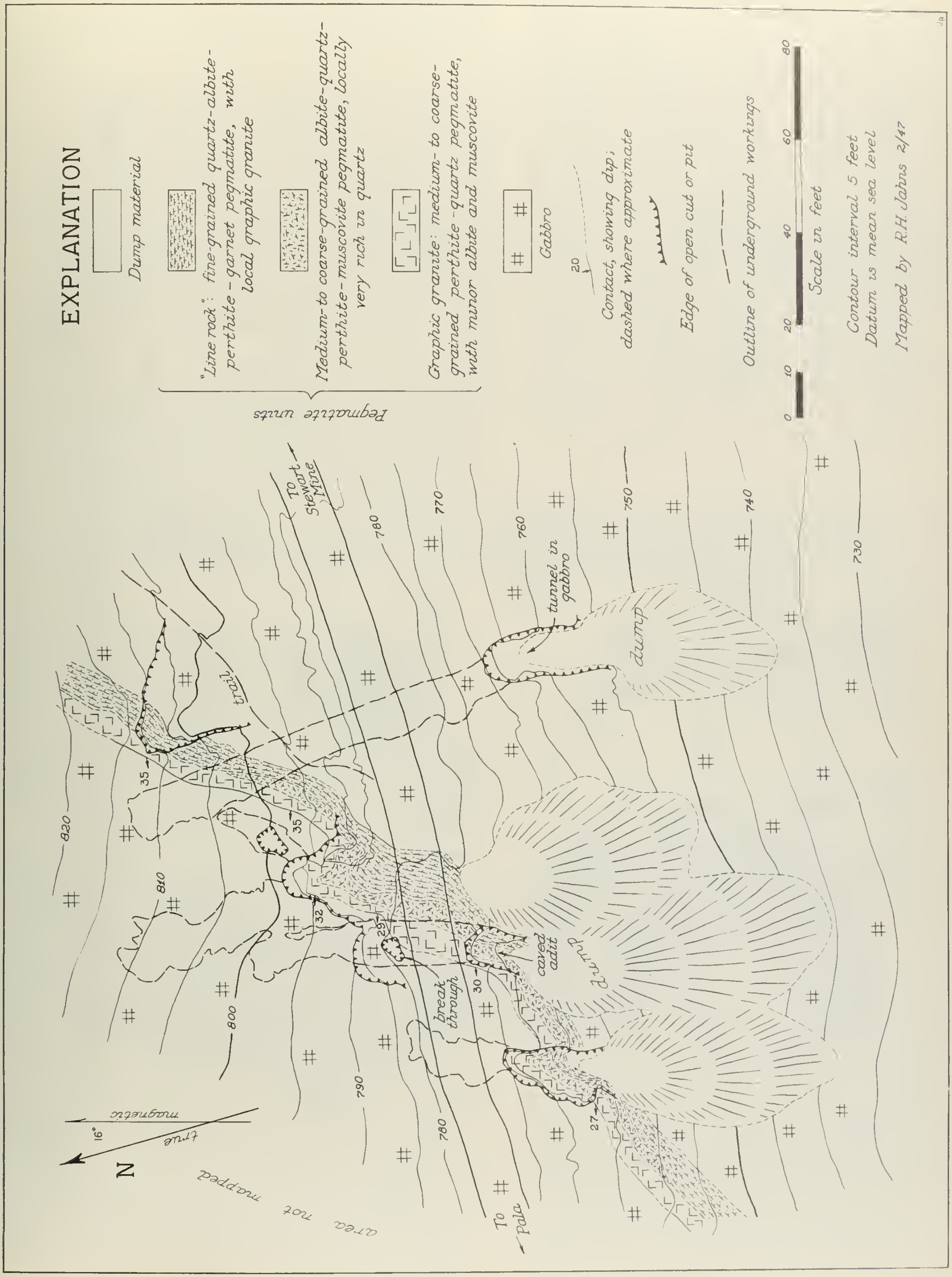


FIG. 32. Geologic map of Mission mine.

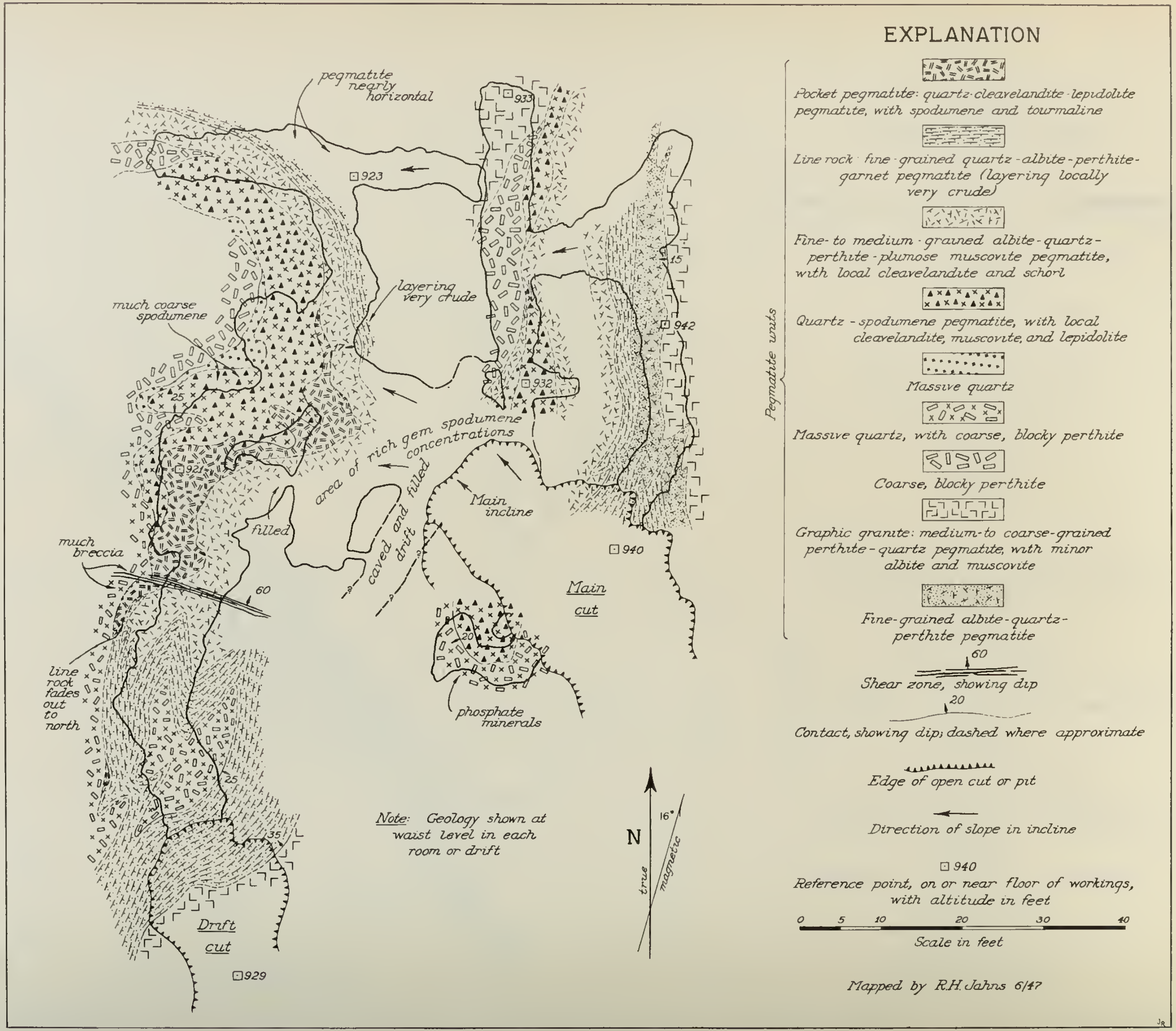


FIG. 33. Plan of main workings, Katerina mine.

strike into fine-grained, sugary rock without layering. It grades downward also into similar homogenous rock, which characteristically forms the lowermost 2 to 4 feet of the dike.

In some places the line rock and associated fine-grained types are in direct contact with the overlying graphic granite, but elsewhere there are intervening zones of very coarse-grained pegmatite. Most common is massive quartz with euhedral to subhedral crystals of perthite. In the southeastern part of the mine area, a series of discoidal masses of quartz-spodumene pegmatite forms the innermost unit of the dike. Most of them are not more than 50 feet in maximum dimension, and not more than 6 feet in maximum thickness. They are best exposed in the underground workings from the southeasternmost cut and from the Main tunnel, and one large segment of this core is poorly exposed on the surface immediately south of the large open cut.

The pattern of the pegmatite zones is complicated here and there by later fracture-filling and replacement units. Most common among them is fine- to medium-grained albite-quartz-perthite pegmatite with plumose muscovite and local cleavelandite and schorl. Much of this rock plainly was formed at the expense of graphic granite, which it transects and corrodes, and in most places it grades upward into graphic granite with clusters of extremely coarse prismatic schorl. A spectacular exposure of stripe rock or zebra rock, comprising many subparallel fracture-controlled albite veinlets in massive quartz, is in the Main tunnel.

The pocket pegmatite, which occurs principally within and along the edges of the quartz-spodumene core segments, consists of lepidolite, albite, alkali tourmaline, quartz, spodumene, beryl, coarse potash feldspar, and several rare accessory minerals. It is best developed along the edges, or thinnest parts of the core segments, where the core and its contained pockets become indistinguishable from one another. Immediately beneath most of the pocket pegmatite is the fine- to medium-grained albite-quartz-perthite-plumose muscovite pegmatite already mentioned.

The internal structure of a part of the Pala Chief dike is shown in plate 10, a typical section through a simply zoned part of the dike. Here a substantial thickness of line rock is overlain by a thin and probably discontinuous spodumene-rich pocket-bearing unit and by the typical hanging-wall unit of coarse graphic granite. The pocket-bearing unit, as in many parts of the dike, is only 1 foot to 3 feet thick, and in most places is between the graphic granite and line rock. At the outcrop of the dike other pocket material, chiefly muscovite, albite, and tourmaline, appears along the hanging wall of a quartz-euhedral perthite unit, but elsewhere similar material is commonly within or along the footwall of such units.

As shown in the section, the chief gem-bearing part of the dike forms a fairly gentle dip slope, which accounts for the frequent designation of the Pala Chief as a "blanket deposit." Contrary to statements commonly made in descriptions of this pegmatite, however, the gently dipping part is not almost wholly isolated by erosion, but instead steepens distinctly as traced southwestward. This steepening carries the dike beneath the southwestern side of the canyon that lies below the mine workings. An essentially dip-slope exposure of hanging-wall graphic granite is widespread in much of the area between the mine dumps and this canyon.

Gem tourmaline is abundant in the pockets of much of the mine area, and particularly in its central and northwestern parts. Farther southeast, however, the most abundant gem material is spodumene, and only in a few places do both these minerals occur in substantial quantities. The tourmaline and spodumene are associated with quartz, beryl, lepidolite, and other pocket minerals. Much of the quartz has formed crystals with milky material in their outermost parts, so that they have a white, enameled appearance. In some parts of the pegmatite, the kunzite and other clear varieties of spodumene represent unaltered parts of much larger lath-shaped crystals encased in massive quartz. Elsewhere, more isolated crystals project inward into clay-filled pockets, and are associated with abundant quartz crystals and scaly aggregates of lepidolite. Some crystals of spodumene and quartz are only partly in contact, but in most places the spodumene is completely surrounded by the quartz, or by quartz and lepidolite.

FIG. 34. Section through adit, El Molino mine, showing down-dip splitting of composite dike.

The Pala Chief pegmatite has been virtually mined out, according to the statements of several men who have examined the mine. The present writers, however, do not subscribe to this interpretation of the available exposures. Recent small-scale mining operations on the knob immediately south of the southeast end of the open cut have demonstrated the existence there not only of the pocket zone, but of excellent gem-quality spodumene very near the surface. This block of ground is approximately 70 feet long as measured in a north-south direction, and may be as much as 6 feet in maximum thickness. It lies immediately west of and slightly higher than the Main tunnel, and could be worked out easily by overhead stoping from this tunnel or by means of a glory-hole. Although at least one large pocket was worked out during the past four years, the likelihood of additional pockets in this block of ground makes the immediate possibilities seem rather attractive. Large crystals of pink beryl also occur in this part of the deposit.

The down-dip extensions of the pegmatite dike also present interesting possibilities. The pegmatite clearly continues for considerable distances along the surface southwestward from the present workings, and the pocket material that was originally prospected appears to have been exposed at the surface only along the crest of a roll in the dike, rather than along the outer edge of an isolated mass of pegmatite. Additional gem-bearing pegmatite may be farther down the dip, either in the relatively steep-dipping segment of the pegmatite, or, more likely, in some flat, or terracelike part of it. Little gem material is exposed along the present outcrop of the dike immediately northeast of the mine area, and the relatively steep dip of this part of the deposit suggests that the chances for good returns in steeply dipping parts down the dip may not be great. The deposit might well be further explored by means of drill holes.

Katerina (Ashley, Catherina, Katrina) Mine

The Katerina mine is low on the slope of Hiriart Mountain, and is near its southwestern ridge. It lies immediately northwest of the Ashley ranch house and about 2 miles east-northeast of Pala, from which it can be reached over well-conditioned roads (pl. 2). Most of the mine workings, which are clearly visible from the valley of the San Luis Rey River to the south, are along the prominent outcrop of a thick and very continuous series of dikes. This dike group, the Vanderburg-Katerina, is traceable eastward and thence northward to points near the summit of Hiriart Mountain, and thence northwestward to the north base of the mountain.

The mine was first opened by M. M. Sickler, and subsequently was worked for many years by him and his sons. Over a long period of intermittent operations, of both formal and ''highgrading'' nature, the deposits in the pegmatite have yielded substantial quantities of lepidolite and gem spodumene, quartz, and beryl. In 1947 the mine was purchased by George Ashley of Pala, who has operated it on a small scale since then. He has obtained several pounds of gem spodumene from two or three small pockets, and some of this material is of exceptionally high quality and attractive color.

The main mine workings extend along the pegmatite group for a strike length of 640 feet. They consist of numerous bench-like open cuts, from many of which short, irregular tunnels and inclines extend northward and northwestward. The principal workings comprise an open cut 40 feet long, 20 to 25 feet wide, and about 30 feet deep at the face; a broad, irregular incline that extends northwestward from this cut; and more recent workings started from a smaller cut to the southwest. The main drift from this second cut trends northward, but its north half is crescentic in plan. Several branch drifts and at least one short incline have been extended from it. Additional underground workings include two drifts at different levels from the Main cut, and very irregular roomlike openings that were developed immediately northwest and west of the Main incline. Most of these stopes are backfilled or caved.

The mining has been done in a highly complex series of juxtaposed pegmatite dikes. Only locally do these dikes diverge and become separated by thin screens and projections of country rock. In the southwestern part of the mine area the dikes are buried beneath a mantle of surface debris, and it is not clear whether they die out abruptly or whether they continue farther westward to points beneath the alluvium of the McGee Creek valley. Toward the east the dikes cross a deep canyon and are traceable along the opposite side of this canyon and the south face of the mountain for half a mile. Along the walls of the canyon are several irregular exposures of pegmatite, and they appear to represent markedly diverging branches from the main pegmatite group. Exposures are not sufficiently continuous to warrant precise interpretations in most parts of this area. At least one dike of major size branches upward from the main group near the southwest end of the mine area. As traced northeastward, this upper dike appears to lie 40 to 100 feet northwest of the main group.

Most of the dikes range in thickness from a few inches to about 32 feet, and the average for the major dikes is about 12 feet. They trend north to north-northwest and dip gently westward, so that their traces are essentially west along the steep south slope of the mountain (pl. 2). At least three major dikes are in the immediate vicinity of the principal mine workings and two of them are exposed in the mine workings themselves. Their presence is indicated not only by local septa of intervening country rock, but by repetitions of their internal units.

The mass of pegmatite that has been of greatest interest during past operations is a large bulge in the middle dike of the group. This bulge has an internal structure markedly similar in most respects to that of the Stewart pegmatite. A hanging-wall unit rich in graphic granite is underlain successively by units of coarse, blocky perthite, massive quartz and large subhedral to euhedral crystals of perthite, massive quartz, and massive quartz with large laths of spodumene. The quartz-spodumene pegmatite, which forms a discoidal core, is about 8 feet in maximum thickness. Its width, as measured in a southwest to northeast direction, is about 70 feet, and its length is at least 85 feet. The lower part of the dike consists of rather crudely formed line rock and fine- to medium-grained albite-quartz-perthite pegmatite containing plumose muscovite and local cleavelandite and schorl. These rocks grade into each other in the outer part of the Main adit. They are also well exposed in the uppermost drift that extends northward from the Main cut.

The Katerina mine has been one of the chief sources of unusual minerals in the district. These minerals are noted in table 3. The typical pocket constituents are present in many of the underground workings, and ordinarily appear as fractured and brecciated aggregates along the edges, top, and bottom of the main and other core segments of quartz-spodumene pegmatite. The largest concentrations of these minerals were encountered in the Main incline and in the roomlike openings immediately to the southwest. They are consistently within the quartz-spodumene core, but appear to be in its outer, rather than in its inner parts. The gem spodumene characteristically occurs as unaltered remnants of much larger spodumene crystals, and appears to be a mineral that is indigenous to the core. It is associated in many places with lepidolite, cleavelandite, quartz, fine-grained, felted aggregates of blue tourmaline, and some white to pink gem beryl. Amblygonite is locally abundant in the outer parts of the quartz-spodumene zone, and occurs also here and there in the massive quartz and the quartz-perthite zones.

The recent operations of Mr. Ashley have been aimed chiefly at exploration of the block of ground that lies immediately west of the crescent-shaped part of the main

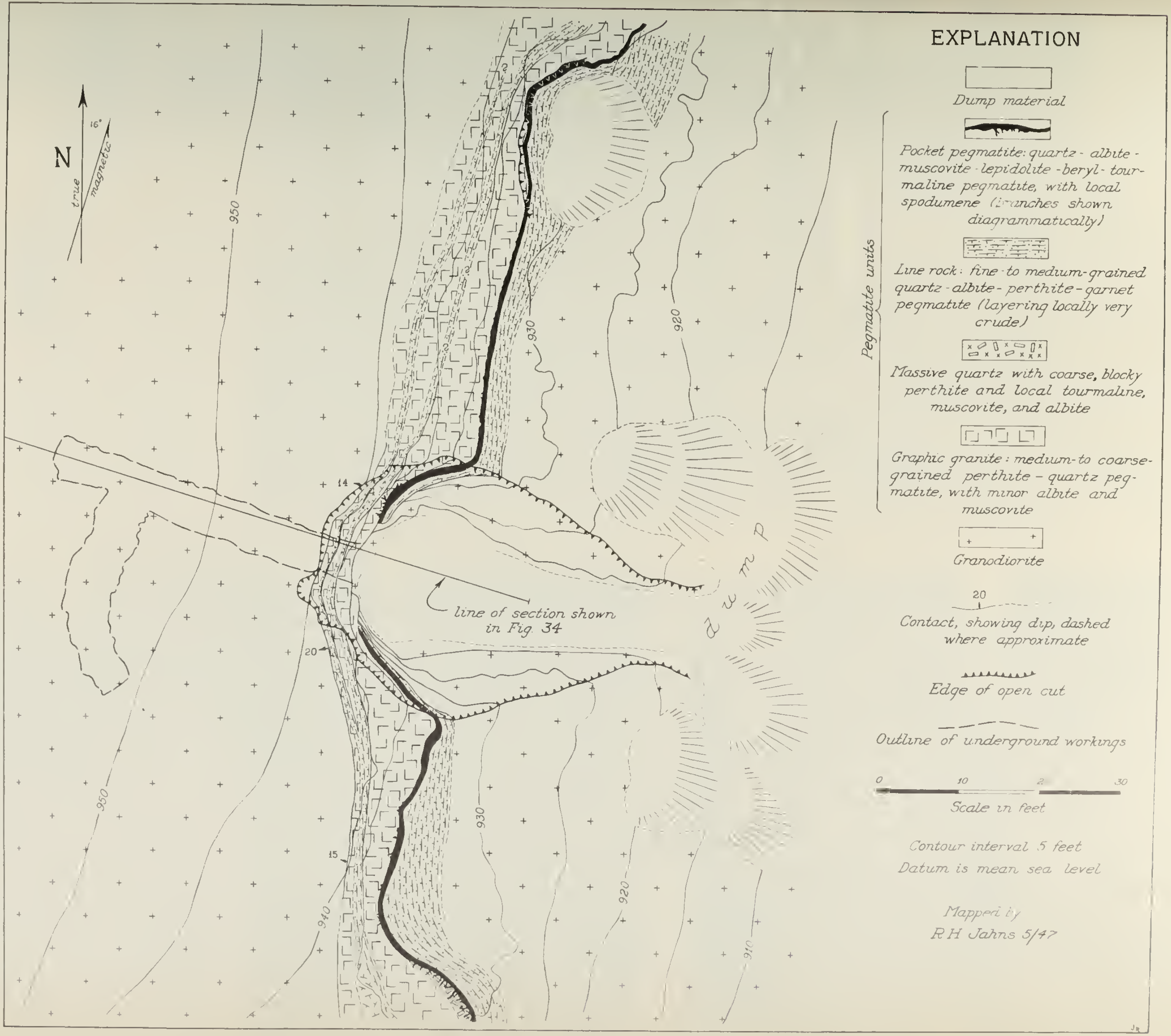


FIG. 35. Geologic map of main workings, El Molino mine.

drift. This ground is along the down-dip extension of the quartz-spodumene zone, and is likely to contain appreciable quantities of gem and other pocket material. Additional exploration might well be aimed at parts of the pegmatite still farther down-dip, and more specifically at the down-dip edge of the main quartz-spodumene mass, where concentrations of minerals similar to the largest pockets in the vicinity of the Main incline might be. Other parts of the mine area that appear to be worthy of further scrutiny are those immediately north of the Main incline and nearby parts of the Main cut.

In addition to the above localities, other parts of the general dike area contain several showings of lepidolite, spodumene, and beryl. Perhaps most noteworthy are the cut and short tunnel at the extreme southwestern end of the area. Here the core is about 15 inches in average thickness, and consists of the typical quartz-spodumene pegmatite with abundant pocket minerals. Both gem spodumene and beryl have been found in this and immediately adjacent parts of the pegmatite. A short distance west of the portal of the Main drift of the Katerina mine is a group of small cuts and appended shallow underground rooms in which kunzite was first discovered. Pocket minerals are exposed in the walls of these workings, which might yield additional material on further prospecting.

El Molino Mine

The El Molino mine is low on the southeast slope of Hiriart Mountain, and can be reached by road and trail from Ashley Ranch house or by trail from the road that skirts the south base of the mountain (pl. 2). The mine workings are in a dike group that crops out prominently along the side of the mountain. The deposit was first opened about 1903, and was worked intermittently by Fred M. Sickler for a period of more than 20 years. It has been known chiefly as a source of excellent pale-yellow, golden, and pink beryl. The property was recently purchased by Norman E. Dawson of San Marcos, who has worked it intermittently and on a very small scale.

The mine is in a group of three juxtaposed pegmatite dikes, which trend north and dip 15° to 25° W. Nearly all the production has been obtained from the lowest dike, which is about 7 feet in average thickness. It is overlain by a dike that is 4 feet in thickness and by another that is 2½- to 3-feet thick; together they form a composite dike that diverges from the main pegmatite in a down-dip direction. The country rock is coarse-grained granodiorite of the Woodson Mountain type, and is a large, upward tapering septum in the gabbro on the southwestern part of Hiriart Mountain.

The two upper dikes are essentially two-unit bodies, and consist of hanging-wall graphic-granite pegmatite and footwall line rock. The internal structure of the lowermost, much thicker dike is somewhat similar, but in addition it contains thin, lenticular core segments of massive quartz with large crystals of perthite. Some of these segments are marked by narrow cavities, especially along contacts between the quartz and feldspar crystals. The cavities are generally ⅛ inch to ¾ inch wide, and some are as long as 2 feet. Many are lined with very much flattened, waferlike quartz crystals and locally with crystals of orthoclase and muscovite. No typical replacement relations appear to be present.

Another variety of pegmatite with local pockets in the central part of the dike is generally at the contact between line rock and the overlying graphic granite. This central unit is remarkably continuous, and in most places is 3 inches to 2 feet thick. It consists chiefly of quartz, potash feldspar, albite, and muscovite, with beryl, bismuth minerals, and sulfide minerals. Some of the beryl occurs as individual crystals and radiating crystal groups in the massive quartz of this unit, and some as colorless to deep-pink tabular crystals that line cavities. This pocket unit is distinct from those in many other pegmatites of the district in that it does not contain appreciable quantities of lepidolite, alkali tourmaline, and similar minerals. Instead, it has the same mineralogy as the small voids in typical core segments of quartz and perthite, and more than anything else it appears to represent chains of such voids, developed on a large scale.

Although an appreciable production of gem beryl was obtained during the previous operations at this mine, it does not appear to offer much possibility of substantial returns from further operations. The pockets that occur in this deposit are excellent examples of a type exploited in several mines in the district, and none of these mines has been a significant source of any gem material except beryl. The pocket pegmatite in such dikes appears to be a much more primary, and hence truly zonal feature than the so-called pocket pegmatite of other dikes, where replacement relations are common.

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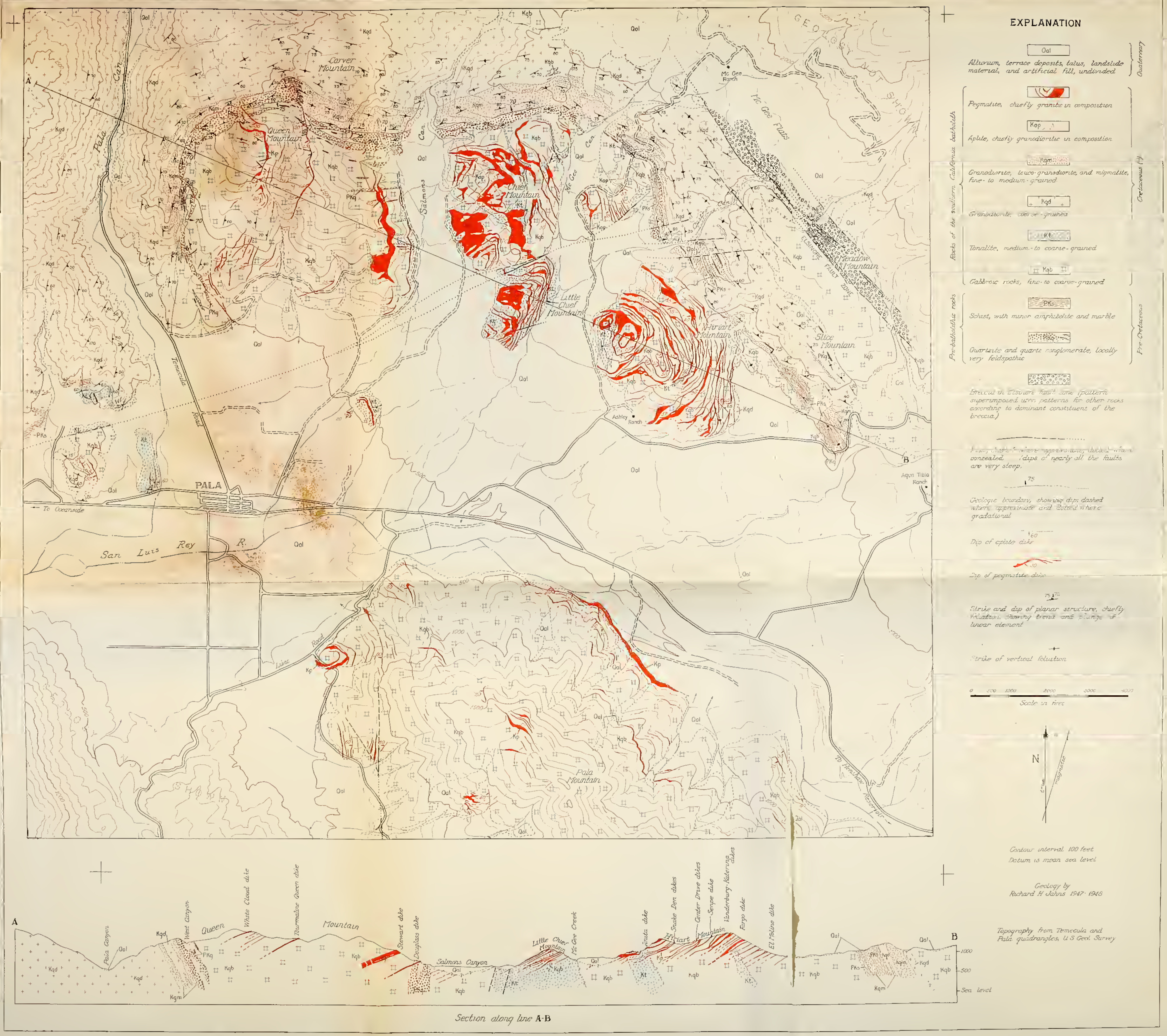
SPECIAL REPORT 7-A, PLATE 1



GEOLOGIC MAP AND SECTION OF THE CENTRAL AND NORTHERN PARTS OF THE PALA PEGMATITE DISTRICT
SAN DIEGO COUNTY, CALIFORNIA

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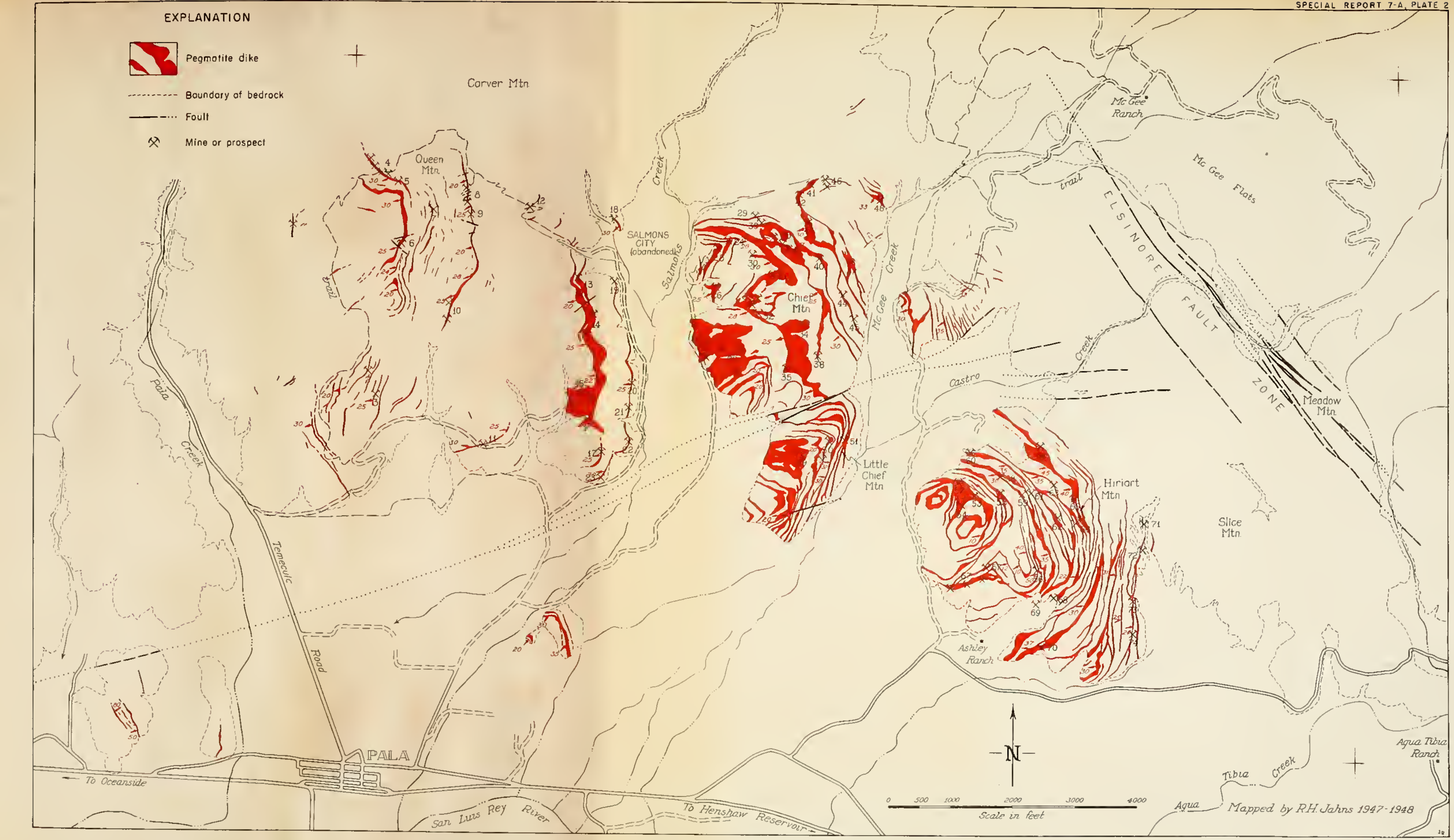
SPECIAL REPORT 7-A, PLATE 2



MAP SHOWING DISTRIBUTION OF PEGMATITE DIKES AND PRINCIPAL MINES AND PROSPECTS

NORTHERN PART OF THE PALA DISTRICT, SAN DIEGO COUNTY, CALIFORNIA

LIST OF MINES AND PROSPECTS

1. West Canyon (Freak) prospect
2. Maud prospects
3. Happy Hooligan prospect
4. Tourmaline King (Wilke, Schuyler) mine
5. Ed Fletcher mine
6. White Cloud (Buster Brown) mine
7. Emerald (Upper Queen) prospects
8. Tourmaline Queen mine
9. Queen Extension prospects
10. Pala View (Sholder-Trotter) mine
11. Mission mine
12. Pala King (Spring Bank, Wedge) prospect
13. North Star mine
14. Gem Star (Loughbaugh) mine
15. Stewart mine
16. Alvarado mine
17. Stewart Extension prospect
18. Homestake prospect
19. North Douglass prospect
20. Douglass Extension prospect
21. Douglass mine
22. Pasture prospect
23. Pala Douglass mine
24. Upper Salmons View prospect
25. Lower Salmons View prospect
26. Redlands King prospect
27. Lower Blanket prospects
28. Upper Blanket prospects
29. Hazel W prospect
30. Canyon King prospect
31. West Knickerbocker prospect
32. Margarita mine
33. Crystal King prospects
34. Dila prospect
35. Butterfly prospect
36. Chief Extension prospects
37. Pala Chief mine
38. Verdant View (Anita) prospect
39. Chief Ridge prospects
40. East Knickerbocker prospect
41. Meadow prospects
42. Poison Oak prospects
43. Ocean View mine
44. Redwing (Redlands) prospects
45. Jackpot Tunnel (Butterfly) prospect
46. North End prospects
47. Goddess prospect
48. Snipe prospect
49. Big Slope prospect
50. Little Chief prospects
51. Clill prospects
52. Chaparral prospects
53. Anita mine
54. Spar Cut prospect
55. Snake Den prospects
56. Center Drive prospect
57. Upper Katerina prospect
58. Senne (Sempa) mine
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60. Pluto prospect
61. White King prospect
62. White Queen mine
63. Spar Pocket mine
64. San Pedro mine
65. Buttercup prospects
66. Vanderburg (Haylor-Vanderburg, Sickler) mine
67. Katerina (Ashley, Catherina, Katrina) mine
68. Hiriart prospects
69. Hiriart mine
70. Fargo mine
71. Canyon prospect
72. Haylor mine
73. Tizmo prospect
74. El Molino mine

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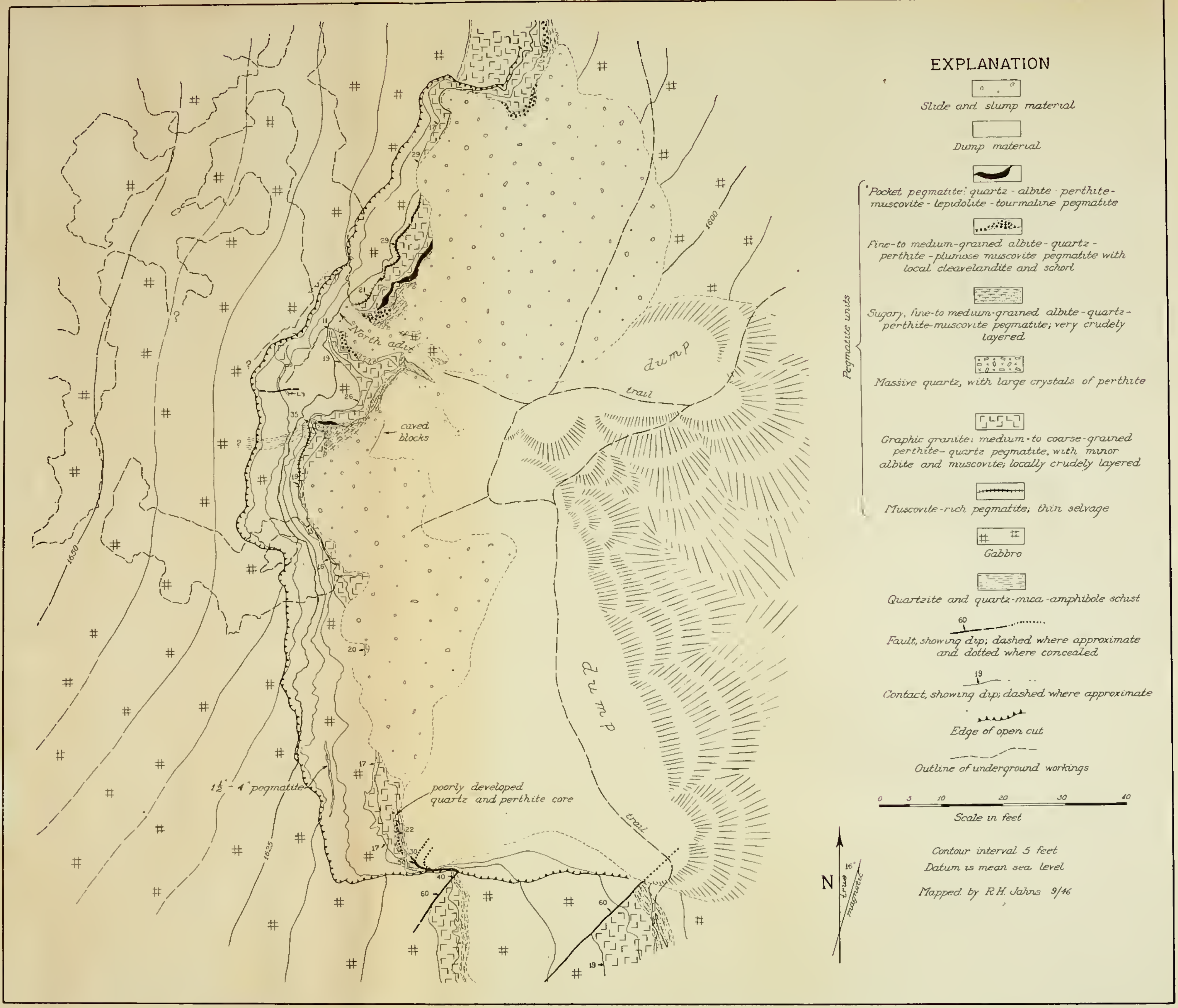
SPECIAL REPORT 7-A, PLATE 3



GEOLOGIC MAP OF SURFACE WORKINGS
TOURMALINE QUEEN MINE
SAN DIEGO COUNTY, CALIFORNIA

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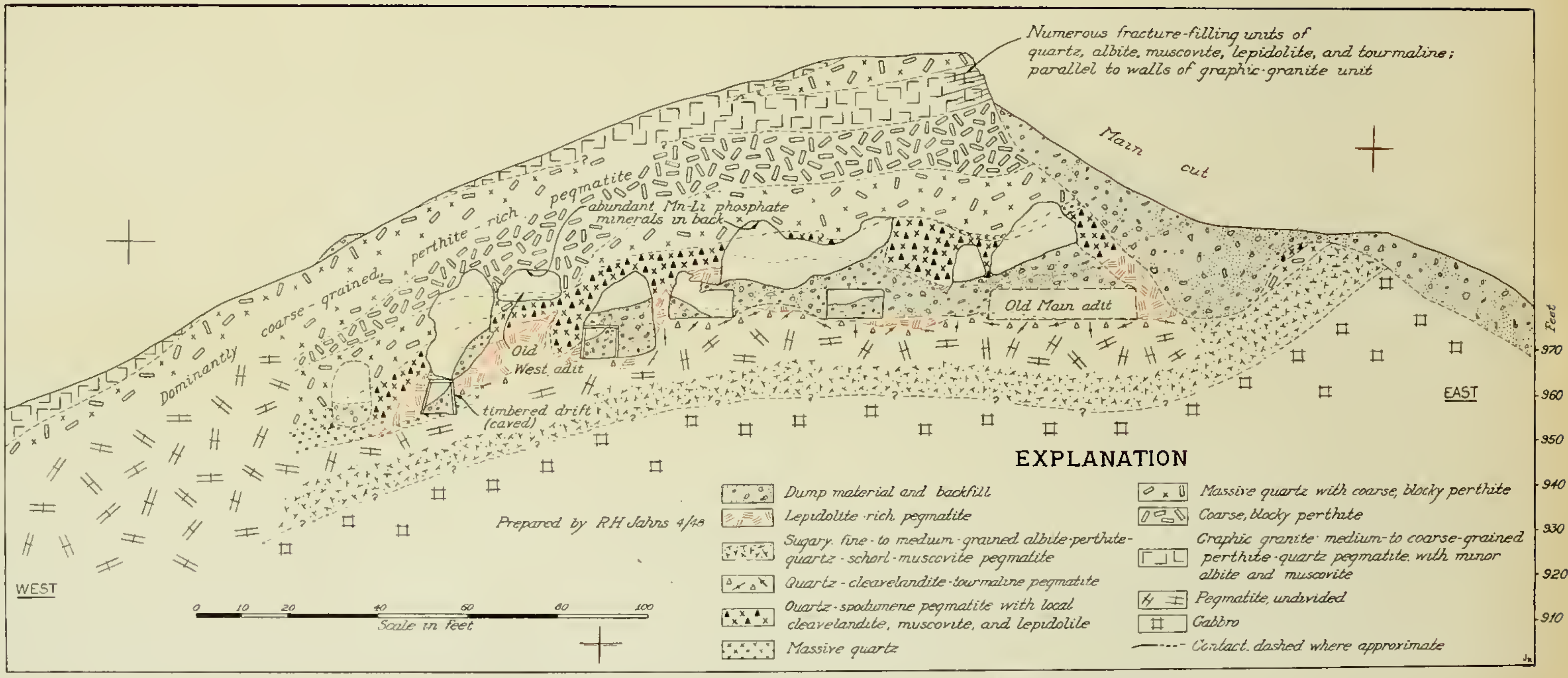
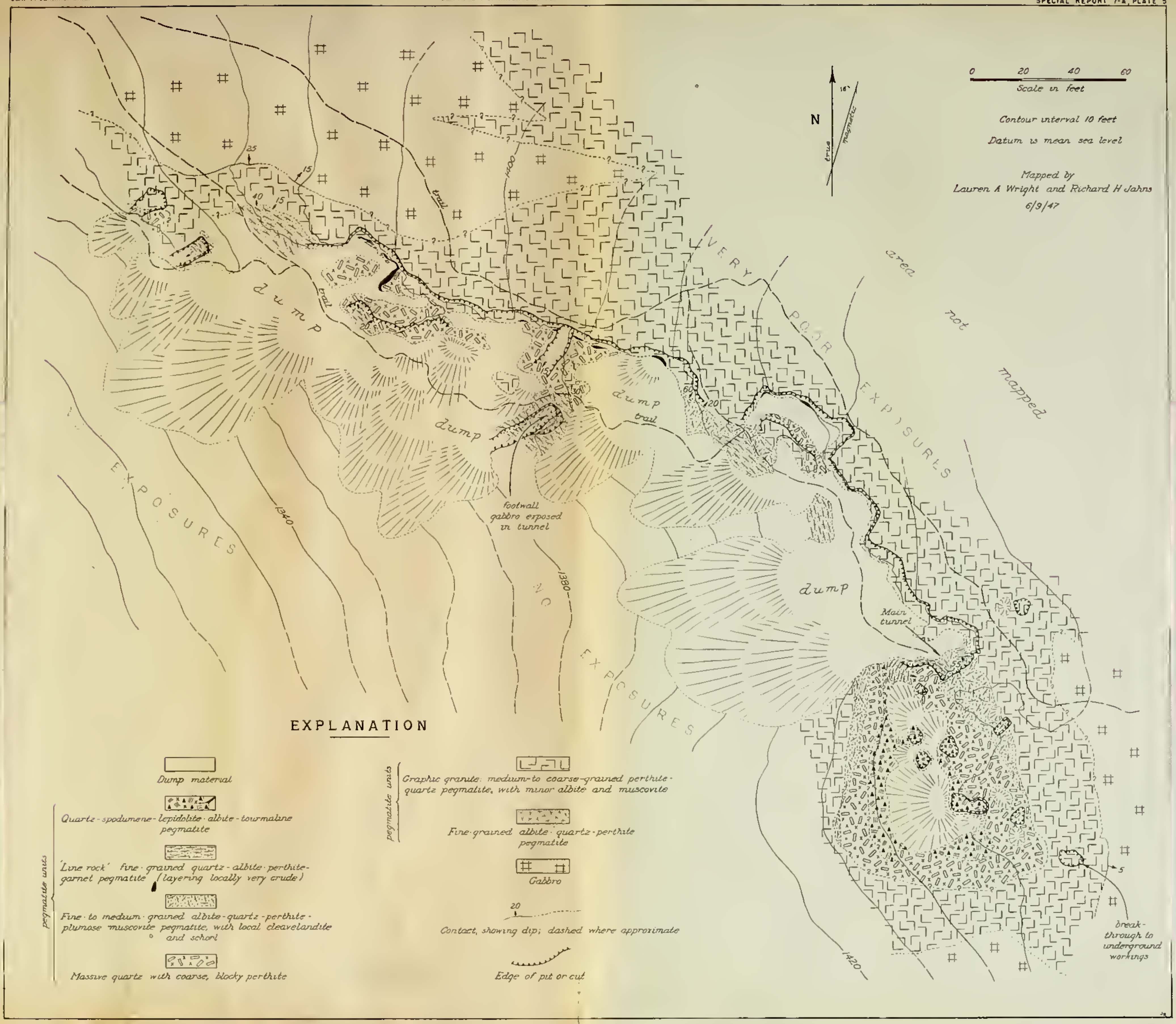
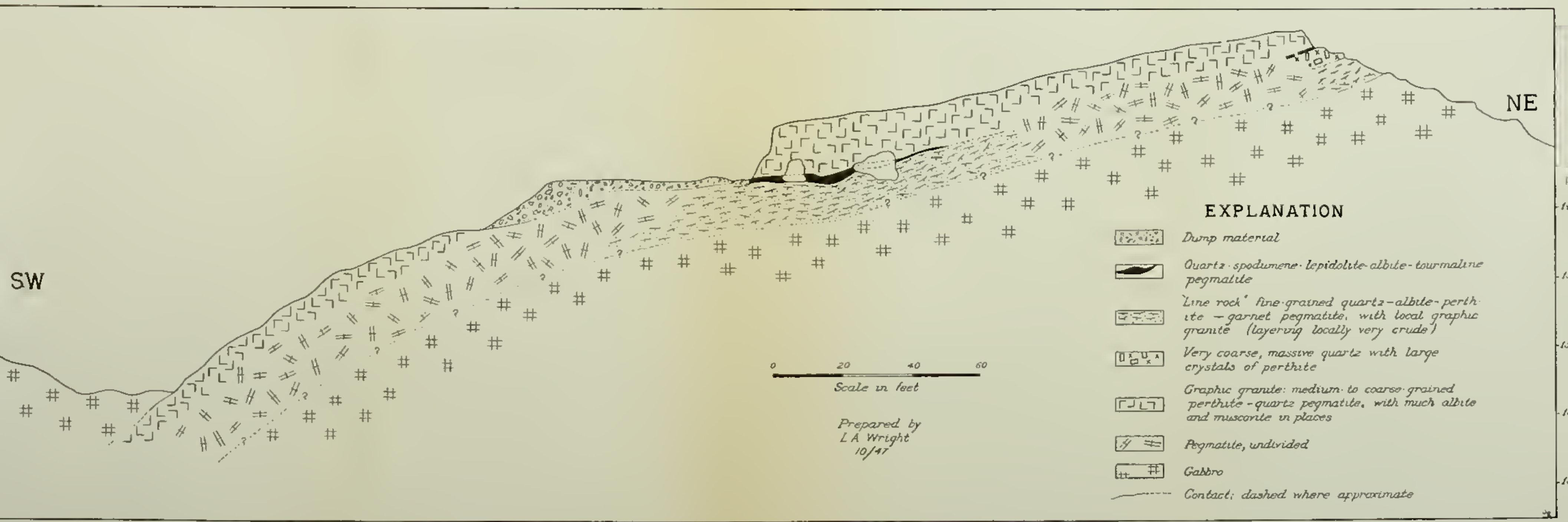
PLAN OF SURFACE AND UNDERGROUND WORKINGS
STEWART MINE
SAN DIEGO COUNTY, CALIFORNIA



GEOLOGIC SECTION THROUGH THE STEWART MINE
SAN DIEGO COUNTY, CALIFORNIA



GEOLOGIC MAP OF SURFACE WORKINGS
PALA CHIEF MINE
SAN DIEGO COUNTY, CALIFORNIA



GEOLOGIC SECTION THROUGH THE PALA CHIEF PEGMATITE
SAN DIEGO COUNTY, CALIFORNIA